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Aquatic Plant Control Research Program

Selective Control of Eurasian Watermilfoil and Curlyleaf Pondweed in Noxon Rapids Reservoir, Montana

Herbicide Small-Plot Evaluations, 2010-2011

Kurt D. Getsinger, John G. Skogerboe, Ryan M. Wersal, John D. Madsen, Justin J. Nawrocki, Robert J. Richardson, and Morgan R. Sternberg

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Environmental Laboratory

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Abstract

Noxon Rapids Reservoir, Montana, is one of several large impoundments on the Lower Clark Fork River, stretching for over 48 km (30 miles) with a surface area of ~ 3,120 ha (7,700 acres). Management strategies were evaluated for their effectiveness in controlling invasive plant problems in the reservoir, specifically with Eurasian watermilfoil and curlyleaf pondweed. A 3-year field program was developed to evaluate the effectiveness of aquatic herbicides to selectively control the invasive plants.

The herbicide endothall (Aquathol® K) was applied to four plots totaling 5.5 ha (13.6 acres) at 3000 µg ai/L (3 ppm); diquat (Reward®) was applied to four plots totaling 3.3 ha (8.1 acres) at 370 µg ai/L (0.37 ppm); and a combination of both products was applied to four plots totaling 4.7 ha (11.5 acres), with endothall at 1500 µg ai/L (1.5 ppm) and diquat at 190 µg ai/L (0.19 ppm). Herbicides were applied by boat using a variable-depth injection system. Aqueous herbicide dissipation was monitored in selected plots. Bulk water exchange processes were also measured. Quantitative surveys were conducted in each plot to assess the plant community at pretreatment, and at 6 weeks and 52 weeks post treatment.

Treatments provided significant reductions in Eurasian watermilfoil (59-69%) and curlyleaf pondweed (40-60%), through 52 weeks post treatment. Both products provided some degree of selective control, with a variety of native plants surviving the treatments.

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP). The APCRP is sponsored by Headquarters, US Army Corps of Engineers (HQ-USACE), and is assigned to the US Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, Mississippi. Funding was provided under Department of the Army Appropriation No. 96X3122, Construction General, the Sanders County Eurasian Watermilfoil Task Force, and the Aquatic Ecosystem Restoration Foundation. The APCRP is managed under the Civil Works Environmental Engineering and Sciences Office, Dr. Alfred Cofrancesco, EL, Technical Director. Dr. Linda S. Nelson was Program Manager of the APCRP. The Program Monitor during this study was Timothy R. Toplisek, HQ-USACE.

The Principal Investigator of this work was Dr. Kurt D. Getsinger, Environmental Processes Branch (EPB), Environmental Processes and Engineering Division (EPED), EL. This work was conducted and the report prepared by Dr. Getsinger and John G. Skogerboe, EPB; Drs. John D. Madsen and Ryan M. Wersal, Geosystems Research Institute, Mississippi State University, Starkville, Mississippi; Justin J. Nawrocki and Dr. Robert J. Richardson, Crop Science Department, North Carolina State University, Raleigh, North Carolina; and Morgan R. Sternberg, School of Aquatic and Fisheries Science, University of Washington, Seattle, Washington.

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Unit Conversion Factors

Multiply	By	To Obtain
acres	0.4046	Hectares
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
ounces (U.S. fluid)	2.957353 E-05	cubic meters

1 Background and Objectives

Background

Noxon Rapids Reservoir, located in northwestern Montana, is one of several large run-of-the-river impoundments on the Lower Clark Fork River system. The reservoir stretches for over 48 km (30 miles), with its upstream boundary at the town of Thompson Falls, Montana. The reservoir has a surface area of ~ 2800 ha (7,700 acres), with its widest fetch at 4 km (2.5 miles) across. At full operating pool, the average depth of the reservoir is 18.5 m (61 ft). The primary function of Noxon Rapids Reservoir is hydro-electric power generation, which is managed by Avista Utilities. Daily dam operations are fairly consistent, but are dependent upon power demands in the regional power grid. Water discharge from the dam during summer months is typically a minimal 1.4–2.8 cms (50-100 cfs) from 2300–0800 hr, followed by a rapid increase in water release to maximum discharges of approximately 750 cms (26,500 cfs)–associated with summertime peak electric power demand in the region - typically between 0900 - 1000 hr.[1]

While the average depth of the reservoir is 18.5 m, the littoral zone of some 790 ha (1,950 acres) has been established from frequent surveys of water transparency and depth distribution of submersed plants, and can extend to depths of 9 m (30 ft) (Madsen and Cheshier 2009; Wersal et al. 2009). These surveys showed a diverse aquatic plant community with over 17 species reported in the reservoir. Dominant native plant species included elodea (*Elodea canadensis*), sago pondweed (*Stuckenia pectinata*), leafy pondweed (*Potamogeton foliosus*), and coontail (*Ceratophyllum demersum*). Species richness was relatively high, with an average of 2.25 species per point, with native species richness at 1.91 species per point (Madsen and Cheshier 2009).

During initial surveys, invasive species were a relatively small component of the plant community, with an average of 0.35 exotic species per point (Madsen and Cheshier 2009). Of the invasive species in the reservoir, curlyleaf pondweed (*Potamogeton crispus*) occurred most often (20% of surveyed points), followed by Eurasian watermilfoil (*Myriophyllum*

[1] Unpublished data, Avista Corporation, Spokane, Washington.

spicatum) (12.3% of littoral points), and flowering rush (*Butomus umbellatus*) (2.3% of points). Vegetation was prevalent in all depths out to 4.6 m (15 ft), common out to 6.1 m (20 ft), and present to 7.3 m (24 ft). Flowering rush was found in depths from 0.3 to 4.3 m. Eurasian watermilfoil was found in depths of 1.5 to 4.9 m, with an optimal depth of 2.4 to 3.3 m. Curlyleaf pondweed was found in depths from 0.61 to 4.9 m, with an optimal range of 1.2 to 3.3 m. In 2008, it was estimated that there was 162 ha (401 acres) of curlyleaf pondweed at the site, 100 ha (247 acres) of Eurasian watermilfoil, and 19 ha (46 acres) of flowering rush. A subsequent survey conducted in 2009 reported that Eurasian watermilfoil covered an estimated 147 ha (364 acres), indicating that this species was expanding within the reservoir (Wersal et al. 2009). Most of the plant stands occur as "blocks" that are 6.1 ha (15 acres) or more in size, or as narrow strips or bands ~ 15-30 m (50-100 ft) wide by 100-200 m long (330-660 ft), located along shorelines. In order to achieve long-term control of these invasive plants in the reservoir, a combination of block and strip management techniques should be developed. If a reservoir-wide management approach is not employed, untreated stands of vegetation will serve as sources for re-infestation of Eurasian watermilfoil and curlyleaf pondweed.

Pursuant to the growing invasive plant problems facing Noxon Rapids Reservoir, i.e. Eurasian watermilfoil and curlyleaf pondweed, Sanders County and the Eurasian Watermilfoil Task Force identified a need to evaluate management strategies for controlling both invasive plant species. A 3-year field program was developed to evaluate the effectiveness of aquatic herbicides to control Eurasian watermilfoil and curlyleaf pondweed in selected areas of the reservoir. In 2009-2010, the work focused on treating blocks of plants (plots 8 ha (20 acres) or more in size) with a combination of systemic and contact herbicides (Getsinger et al. 2013).

In 2010-2011, the work focused on treating shoreline strips (bands) of vegetation 0.8-1.2 ha (2-3 acres) in size utilizing quick-acting contact herbicides. These strips are generally in unprotected areas of the reservoir and are subject to greater water exchange processes than the larger populations that were treated in 2009. The smaller strips also tend not to retain the herbicide as well as larger contiguous beds of Eurasian watermilfoil. A treatment "edge effect" occurs in small plots, where a larger proportion of untreated water outside of the treated plot provides opportunities for herbicide dilution as untreated water quickly circulates through the treated strips. The higher water exchange and smaller size of

the strip-plots reduces herbicide contact and exposure time around target plants, and can reduce treatment efficacy, particularly if longer-acting systemic herbicides are used. Therefore, contact herbicides would be a better control option in these strip populations, as these compounds generally require less contact time with target plants to achieve control.

Diquat and endothall are two aquatic contact herbicides that have been evaluated for Eurasian watermilfoil control (Parsons et al. 2004, Wersal et al. 2010). Diquat requires less contact time than endothall, but can be less species-selective as well (Skogerboe et al. 2006). Conversely, endothall typically requires slightly longer contact times, but can be species-selective depending upon the herbicide concentration used (Skogerboe and Getsinger 2002). Also, there has been renewed interest over the past several years in using herbicide combinations in an attempt to increase herbicide efficacy, especially by reducing the contact time needed for effective control. Madsen et al. (2010) combined endothall with the slower-acting system products, 2,4-D and triclopyr, to take advantage of the rapid action of endothall, while maintaining systemic control with 2,4-D and triclopyr. Combining diquat with endothall may result in greater species selectivity than using diquat alone.

Combinations of the aquatic herbicides triclopyr and endothall effectively and selectively controlled Eurasian watermilfoil in 6- to 8-ha (15- to 20-acre) plots in Noxon Rapids Reservoir for up to two growing seasons - year of treatment and one year post treatment (Getsinger et al. 2013). While curlyleaf pondweed populations were controlled in the year of treatment, they were not controlled at 1 year post treatment. Long-term management of curlyleaf pondweed depends upon more than removing seasonal standing crop biomass. These strategies must include controlling the production and sprouting of vegetative turions. Early-season treatment with herbicides can effectively control curlyleaf pondweed and prevent turion production, while preserving native plant populations that are still dormant (Woolf 2009). Herbicide application timing will be critical to accomplish that plant life cycle management strategy. Abundant fish and wildlife habitat was maintained in herbicide-treated plots, as minimal impacts occurred to native plant populations, and there were no impacts on dissolved oxygen levels. As opposed to the treated plots, native plant populations remained suppressed in the untreated plots, and the vegetative community continued to be dominated by Eurasian watermilfoil.

Understanding bulk water exchange processes in treatment areas can provide guidance for prescriptive management strategies and improved invasive plant control using herbicides. Variable-depth application techniques can deliver a greater proportion of herbicides to the deeper zones of the water column. This delivery method should improve efficacy and reduce the amount of herbicide required to achieve plant control. Herbicide evaluations should be used to develop strategies for controlling Eurasian watermiloil and curlyleaf pondweed in narrow shoreline areas to compliment management activities on larger plant stands. If not managed, these smaller areas will provide sites for reestablishment of invasive plants into areas previously controlled, as well as into areas not yet infested.

Objectives

The primary objectives of this work were to:

1. Evaluate the species-selective control of shoreline populations of Eurasian watermilfoil and curlyleaf pondweed growing in narrow strips using contact herbicides in Noxon Rapids Reservoir, and
2. Utilize results of these evaluations to provide guidance for submersed invasive plant management on Noxon Rapids Reservoir, and similar run-of-the-river impoundments in the Pacific Northwest.

2 Description of Small Plots

Vegetation strips used in theses evaluations were identified using a combination of point intercept surveys conducted within submersed plant stands in 2008 and 2009, as well as aerial imagery of the reservoir. Based on this information, 16 small linear plots, or strips, were selected for the herbicide evaluations in July 2010. General locations of these plots in the reservoir are shown in Figure 1. These treatments were targeted for Eurasian watermilfoil and curlyleaf pondweed stands growing in upstream areas of the reservoir. Control of these plant stands will limit the continued re-introduction of the target plants to downstream areas. Plots were selected based upon onsite water exchange estimates using tracer dye and experience with water exchange processes encountered during the 2009-2010 block treatment evaluations. Additionally, daily discharge patterns from Noxon Reservoir dam were utilized to minimize water exchange conditions in areas selected for herbicide treatments.

Plots were situated along shoreline areas in the reservoir that were infested with mixed stands of Eurasian watermilfoil and curlyleaf pondweed, but also contained numerous species of desirable native submersed plants (Table 1). These narrow strips of vegetation were typically 300-450 m (1000-1500 ft) long by 15-30 m (50-100 ft) wide, and ranged from 0.5 to 1.9 ha (1.2 to 4.8 acres) in size, with an average size of 1.2 ha (2.85 acres) (Figures 2-5; Table 2). The plots were located in the littoral zone of the reservoir with average depths ranging from 1.7 to 4 m (average depth of all plots was 2.7 m). The shore-side boundaries of the plots were shallow (0.3-1 m) and water depth decreased rapidly to more than 6 m (20 ft) just beyond the reservoir-side (open water) boundaries of the plots. The plots comprised a total of 18.6 ha (46 acres), of which 13.4 ha (33 acres) were treated with herbicides.

To prevent herbicide cross-contamination among plots, untreated buffer strips (approximately 0.8 ha in size) were located between treatments. By utilizing these buffers, herbicide treatment plots were separated by an average distance of 455 m (1500 ft). In addition, untreated reference plots were separated from herbicide treatment plots by an average distance of 5790 m (19,000 ft). All plots and buffers were established by boat using Global Positioning System (GPS) technology. Locations of the herbicide-treated plots, the untreated reference plots, and the untreated buffer strips are shown in Figures 1-5.

Figure 1. Areas designated for herbicide small-plot evaluations, Noxon Rapids Reservoir, MT, 2010-2011.

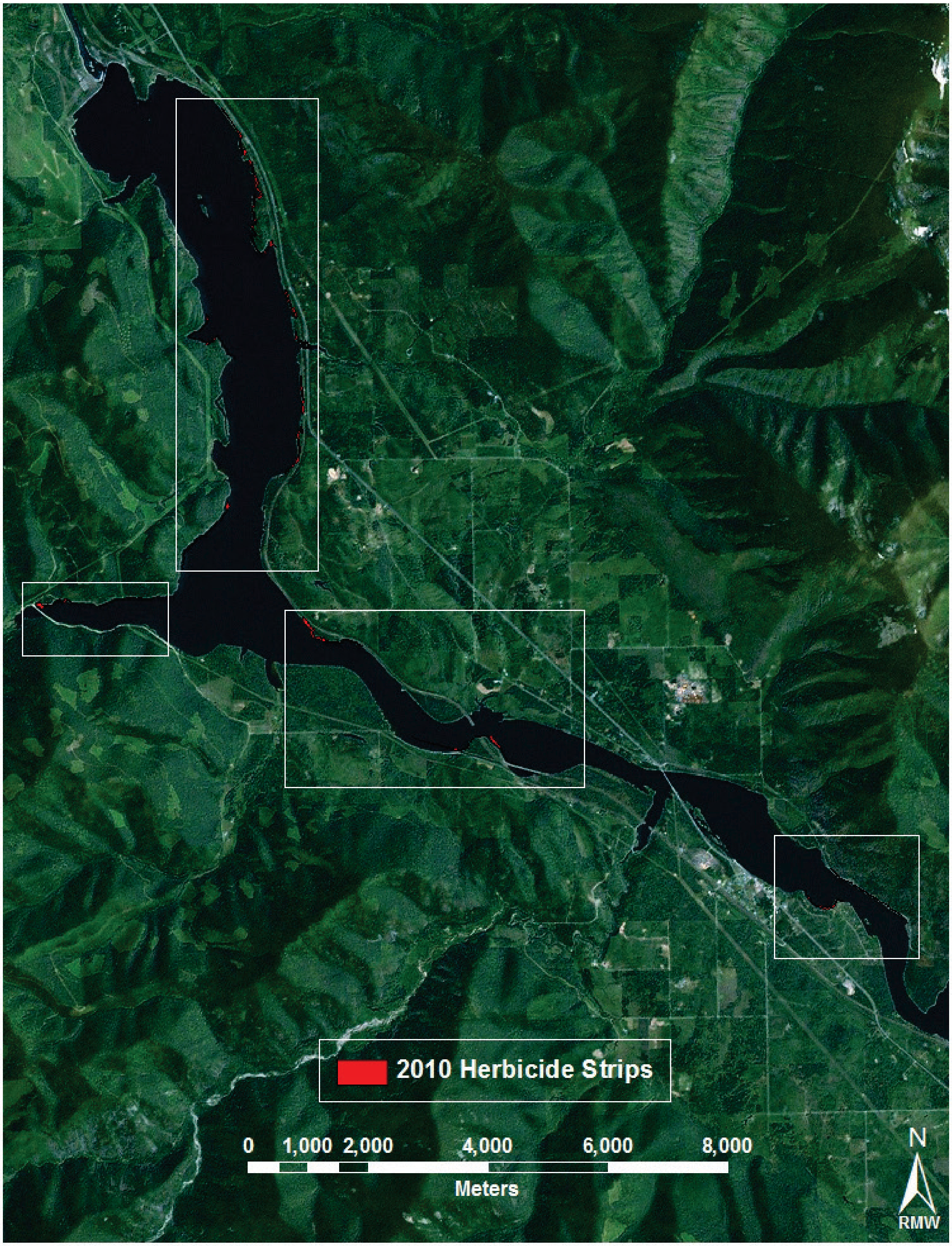


Figure 2. Location of vegetation strips 1 through 11, and 22 through 24, in Noxon Rapids Reservoir, MT, 2010-2011. These strips represented herbicide-treated plots and untreated buffer zones.

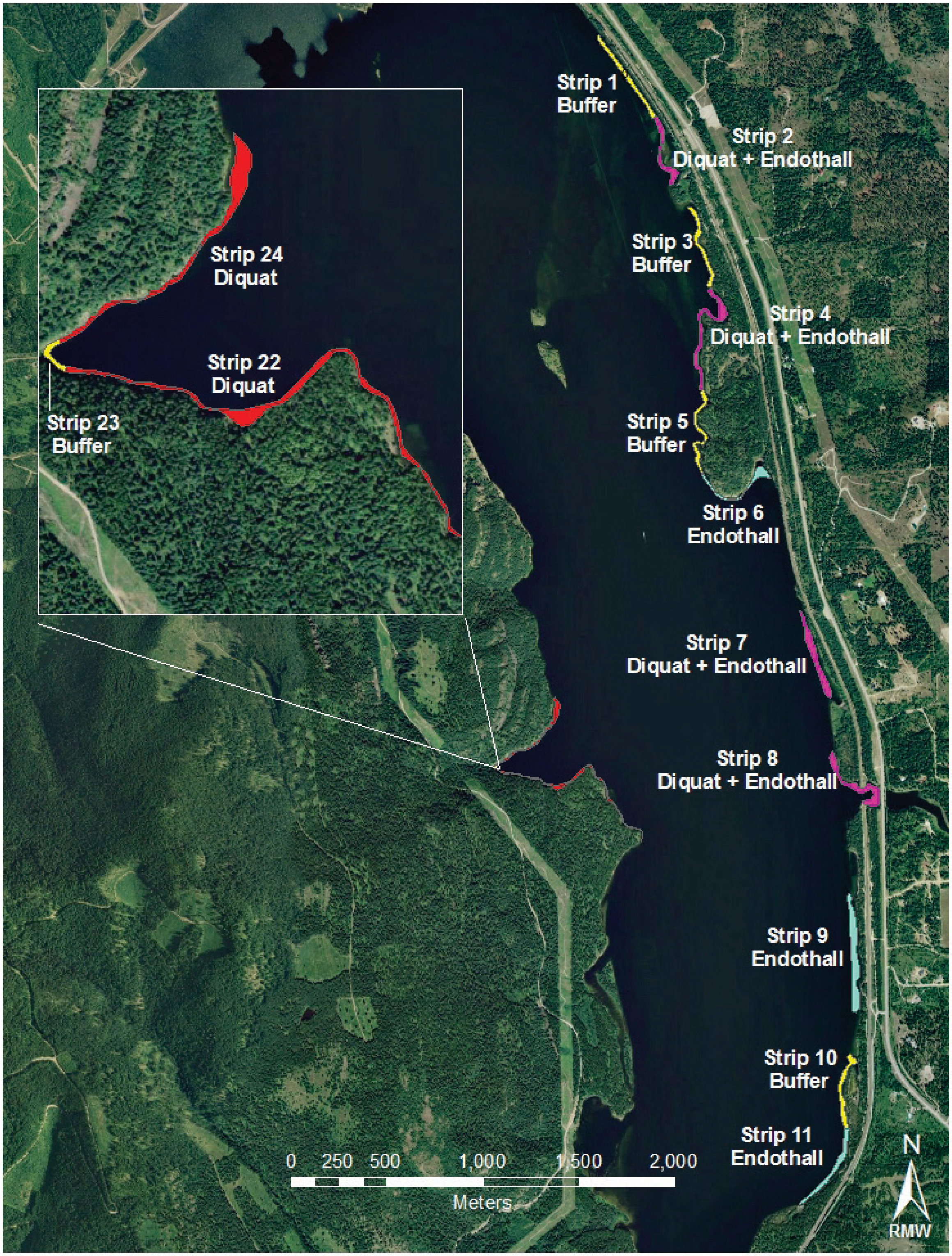


Figure 3. Location of vegetation strips 12 and 13, and 16 through 18, in Noxon Rapids Reservoir, MT, 2010-2011. These strips represented untreated reference plots and buffer zones.

Figure 4. Location of vegetation strips 14 and 15 in Noxon Rapids Reservoir, MT, 2010-2011. These strips represented an untreated reference plot and an untreated buffer zone.

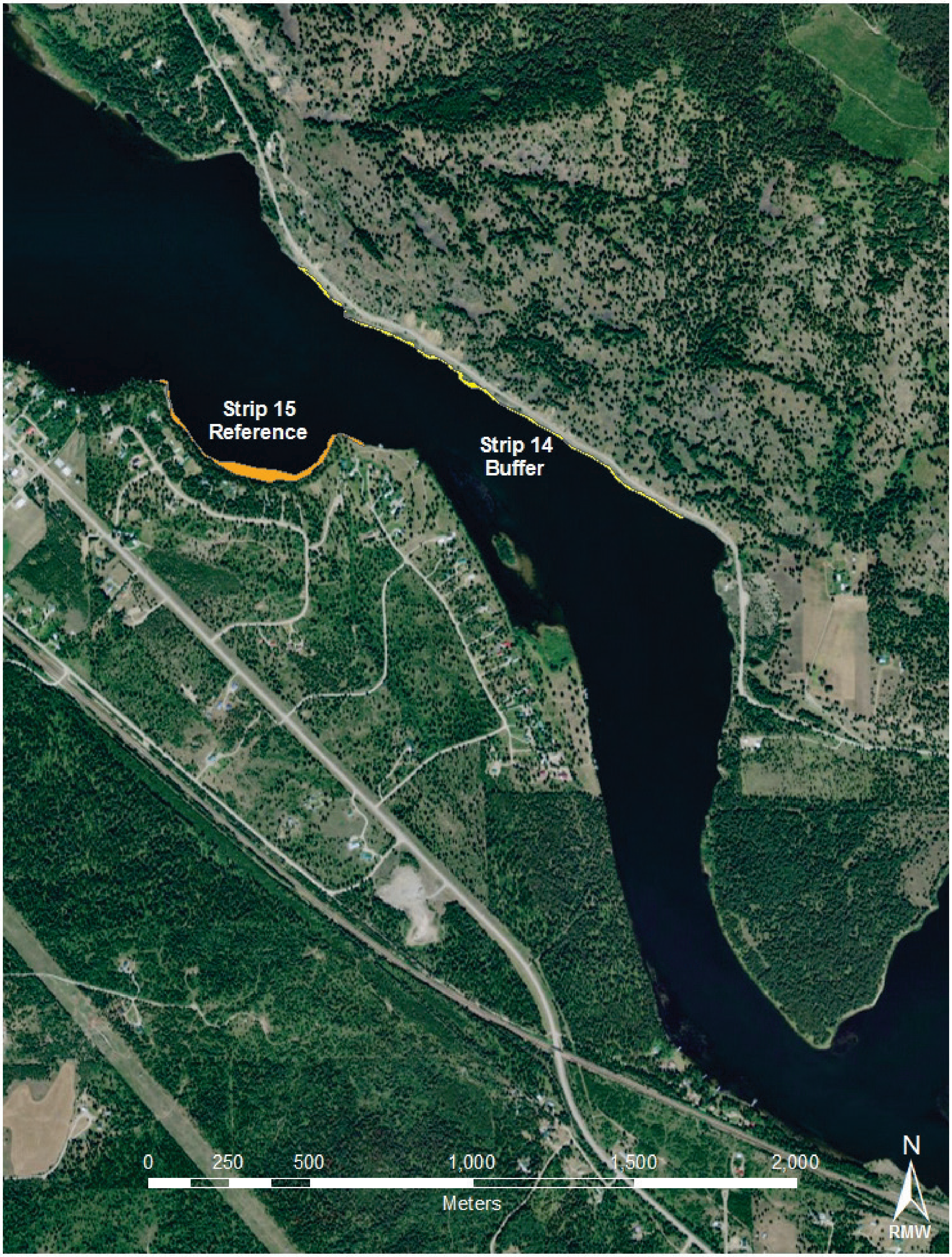


Figure 5. Location of vegetation strips 19 through 21 in Noxon Rapids Reservoir, MT, 2010-2011. These strips represented herbicide-treated plots.

Table 1. Aquatic plants occurring in small plots prior to herbicide evaluations in Noxon Rapids Reservoir, MT, July 2010.

Plant Species	Common Name
Butomus umbellatus L.	Flowering rush
Ceratophyllum demersum L.	Coontail
Chara sp.	Muskgrass
Elodea canadensis Michx.	Elodea
Heteranthera dubia (Jacq.) Small	Water stargrass
Myriophyllum sibiricum Komarov	Northern watermilfoil
Myriophyllum spicatum L.	Eurasian watermilfoil
Najas flexilis L. (Willd.) Rost & Schmidt	Slender naiad
Nitella sp.	Stonewort
Potamogeton crispus L.	Curlyleaf pondweed
Potamogeton foliosus Raf.	Leafy pondweed
Potamogeton illinoensis Morong	Illinois pondweed
Potamogeton praelongus Wulf.	Whitestem pondweed
Potamogeton richardsonii (Ar. Benn.) Rydb.	Clasping-leaved pondweed
Ranunculus aquatilis L.	White water-buttercup
Stuckenia pectinata (L.) Börner	Sago pondweed
Vallisneria Americana Mich.	Wildcelery

Table 2. Site characteristics of vegetation strips used for herbicide plot evaluations in Noxon Rapids Reservoir, MT, 2010-2011.

Treatment[1]	Plot No.[2]	Treatment Date 2010	Herbicide (µg ai/L)[3]	Hectares	Avg. Depth (m)[4]		Distance to Closest Herbicide Plot (m)[5]	Time + Application Duration	Wind (kph)	Reservoir Discharge (cms)[6]
End	6	8/2	3.0	0.7	4.0		450	0740 h 20 min	S 5.3	247
End	9	8/2	3.0	1.9	3.2		503	0813 h 45 min	0	247
End	11	8/2	3.0	1.0	3.2		602	0912 20 min	0	361
End	19	8/2	3.0	1.9	1.7		518	1028 h 28 min	W 7.1	455
Diq	20	7/30	0.37	0.9	1.9		450	0730 h 12 min	W 13.7	178
Diq	21	7/30	0.37	1.2	2.4		899	0754 h 14 min	SE 7.9	228
Diq	22	7/30	0.37	0.6	3.6		198	0832 h 21 min	W 4.8	228
Diq	24	7/30	0.37	0.5	3.0		198	0859 h 6 min	SE 6.4	430
Diq + End	2	7/28	0.19 + 1.5	0.8	1.9		579	0804 h 5 min	S 7.1	470
Diq + End	4	7/28	0.19 + 1.5	1.4	2.4		579	0728 h 13 min	SW 1.8	420
Diq + End	7	7/28	0.19 + 1.5	1.3	2.8		305	0947 h 17 min	SE 7.7	471
Diq + End	8	7/28	0.19 + 1.5	1.2	2.9		305	0857 h 19 min	0	472
Ref	12		0.0	1.5	3.1		2195			
Ref	13		0.0	0.9	2.2		3002			
Ref	15		0.0	1.3	2.6		5852			
Ref	16		0.0	1.4	2.0		12253			
Buf	1		0.0	1.0	2.5		Adjacent			
Buf	3		0.0	0.8	2.5		Adjacent			
Buf	5		0.0	1.0	5.7		Adjacent			

Treatment[1]	Plot No.[2]	Treatment Date 2010	Herbicide (µg ai/L)[3]	Hectares	Avg. Depth (m)[4]		Distance to Closest Herbicide Plot (m)[5]	Time + Application Duration	Wind (kph)	Reservoir Discharge (cms)[6]
Buf	10		0.0	1.0	3.3		Adjacent			
Buf	14		0.0	1.1	2.6		Adjacent			
Buf	17		0.0	0.6	1.8		Adjacent			
Buf	18		0.0	0.8	2.8		Adjacent			
Buf	23		0.0	<0.1	3.4		Adjacent			

[1]End=Endothall; Diq=Diquat; Ref=Untreated References; Buf=Treatment Buffer

[2]See attached maps for treatment location in reservoir.

[3]Rhodamine WT dye applied at 10 µg ai/L with all herbicide applications.

[4]Water depths were recorded on 7/22/2010 and 7/23/2010.

[5]The reservoir is at least 1219 m wide (shoreline-to-shoreline) at narrowest point.

[6]Avista Corporation.

3 Materials and Methods

Herbicide treatments

Since water exchange processes in the plots were expected to greatly reduce potential herbicide contact time, the following treatment protocol was developed to utilize applications of the quick-acting contact aquatic herbicides, endothall and diquat. In addition to water exchange factors, results from previously conducted small-scale herbicide concentration and exposure time studies were used to select application rates (Skogerboe and Getsinger 2002, Parsons et al. 2004, Skogerboe et al. 2006, Wersal et al. 2010). Products evaluated included a liquid formulation of endothall (Aquathol® K) applied to achieve an aqueous concentration of 3000 µg ai/L (3 ppm), 60% of maximum label rate; a liquid formulation of diquat (Reward®) applied to achieve an aqueous concentration of 370 µg ai/L (0.37 ppm), maximum label rate; and a combination of both products, with endothall at 1500 µg ai/L (1.5 ppm) and diquat at 190 µg ai/L (0.19 ppm), as shown in Table 2. All treatments were replicated four times, as four separate strips of vegetation. Herbicide treatments were randomly assigned to each strip with the exception of diquat, which was applied in strips along sheer rock faces where the Eurasian watermilfoil was growing from cracks in the rocks or in deeper water – the only avenue for maximizing herbicide contact time in these areas. Reference plots were located as far upstream from treatment areas as possible to eliminate the potential of herbicide movement into these areas. The reference plots were included to indicate what would happen by choosing a “no management” approach, in comparison to treated plots. If the target species remained constant, or increased, through time, in the reference plots, then it can be reasonably assumed that the herbicides were having an effect in the treatment plots. A total of 5.5 ha (13.6 acres) were treated with endothall alone; a total of 3.3 ha (8.1 acres) were treated with diquat alone; and a total of 4.7 ha (11.5 acres) were treated with the endothall + diquat combinations. Four untreated reference plots were used for comparison of herbicide efficacy, and comprised a total of 5.1 ha (12.5 acres).

Herbicide applications were conducted by Clean Lakes, Inc. (Coeur d’Alene, Idaho), and information on state permits, environmental assessments, and herbicide labels required for treatments is presented in a document compiled by Clean Lakes, Inc. (2010). From 28 July through 2 August 2010,

herbicides were applied by boat to the plots using a variable-depth precision injection system (LittLine®, Clean Lakes, Inc.). This application process simulated an operational-scale liquid aquatic herbicide treatment. The injection system was calibrated to deliver product to the bottom 0.3-1 m of the water column – targeting the submersed plants in the lower one-third of the water column. Herbicides were applied evenly across each plot, and were applied simultaneously with the inert tracer dye, rhodamine WT (RWT). Details of dye applications are presented below.

Herbicide applications were conducted during the morning hours (~0703–1030 hr) of 28 and 30 July, and 2 August (Table 2). At these times, reservoir discharges ranged from 178 to 472 cms (6,280 to 16,670 cfs), and averaged 350 cms (12,378 cfs). Peak hourly discharges for those dates occurred from 1200–1900 hr, at roughly 700 cms (25,000 cfs). Winds were generally light and variable during applications, and measured at < 8 kph (5 mph).

Aqueous herbicide residues

Water samples were collected to monitor endothall residues in Plots 4, 6, 8, and 11, and to monitor diquat residues in Plots 20 and 22. The surface area of each of these plots was divided into three equal zones and a water sampling station for monitoring residues was established in the center of each zone. Herbicide residue samples were collected in the water column at three depths: 0.3 m below the surface (S), mid-depth (M), and 0.3 m above the bottom (B) at each station. Sampling events immediately after the entire application process had been completed - denoted as 0 hr after treatment (HAT) - and at approximately every 1 to 1.5 hr thereafter up to 9.5 HAT, provided six to seven post-treatment periods.

For endothall analysis, water samples were collected in 60-ml Nalgene® wide-mouth, amber, high-density polyethylene bottles. Samples were stored on ice and shipped chilled to the analytical laboratory at the US Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi. Samples were frozen immediately upon receipt at the analytical laboratory. At least 48 hr prior to analysis, samples were transferred to the refrigerator to thaw. Samples and analytical test kits were removed from the refrigerator at least 1 hr before analysis to ensure they were at room temperature.

The RaPID Assay® Endothall Test Kits (Strategic Diagnostics Incorporated (SDIX), Newark, Delaware) were used to quantify endothall acid residues.

Analytical kits utilize the principles of enzyme-linked immunosorbent assay (ELISA) to quantify herbicide residues. Samples were commonly diluted at either a 10:1 or 20:1 concentration. A sample aliquot was added to test tubes along with an enzyme conjugate, followed by the addition of paramagnetic particles. The herbicide and the conjugate compete for binding sites on the paramagnetic particles. Samples were incubated for 20 min, after which a magnetic field was applied to the tubes to allow for decanting of any unbound reagents. Presence of endothall was detected by adding the enzyme substrate (hydrogen peroxide) and chromogen, generating a colored product. The solution was incubated for 15 min and terminated with addition of acid. The level of color development was inversely proportional to the concentration of the herbicide in the water.

Quantification was achieved by first producing a standard curve using standards provided with each test kit. One group of nine standards was analyzed with each set. Computer software furnished with the kits provided a means of obtaining the curve and calculating results. All unknown samples were analyzed against standard curves, and a new curve was constructed for each set of samples analyzed. Absorbance (450 nm) was measured using an RPA-I Photoanalyzer™ (SDIX). Standard curves were constructed using linear regression after a log/logit transformation of the concentration and absorbance values, respectively. Assay results were acceptable if the correlation of standard curves was more than 0.990. If the reported concentration was outside of acceptable parameters as deemed by test kit procedures, the test was repeated. At least one sample was spiked with a known concentration of herbicide and percent recovery was reported. The error average for all samples was less than 5%.

For diquat analysis, water samples were collected in 250-ml Nalgene® wide-mouth, amber, high-density polyethylene bottles. Samples were stored on ice, then shipped overnight (chilled with blue ice packets), within 5 days of collection, to Pacific Agricultural Labs (Portland, Oregon). Upon arrival at the laboratory, the samples were acidified with hydrochloric acid to pH 2. All samples were analyzed according to the process presented in Munch and Bashe (1997). The lower limit of detection was 5 µg/L (ppb). Because the 5-µg/L reporting limit was sufficiently low for this project, a direct injection analysis was the most effective method for analyzing the samples. The upper limit for quantitation is 1 billion µg/L (100%). Quality assurance/quality control (QA/QC) procedures were also conducted according to USEPA method 549.2. Specifically, method blanks, blank spikes (up to five times

the reporting limit), and matrix spike/matrix spike duplicates were used within every extraction batch. All QA/QC results were included in the final report. The range of recovery within spiked samples was 74 to 104%, and the average recovery from spiked samples was 90%. Nothing was ever recovered from blank tests. A recovery of more than 100% is possible when the amount recovered is lower than the amount spiked.

Bulk water exchange processes

The inert tracer dye, RWT, was applied at the rate of 10 µg/L (ppb) based on water volume of each plot (calculated as 1.7 fl oz concentrated dye per acre-foot – a standard volume expression for aquatic herbicide applications). Rhodamine WT dye is approved by the USEPA for use in surface waters, and at the nominal aqueous concentrations used for this study (10 µg/L or less), the dye is harmless to humans, fish, and wildlife. This dye is routinely used in water tracing studies in the Pacific Northwest by agencies such as USACE, US Fish and Wildlife Service (USFWS), and US Geological Survey (USGS). At the nominal treatment concentrations, the pinkish-colored dye is practically invisible to the naked eye, but can be measured using calibrated fluorometers at levels near 0.1 µg/L. Dissipation of the dye was used to determine bulk water exchange processes in the herbicide-treated plots during treatment and post-treatment periods. This liquid dye was also applied with the variable-depth injection system as described above. Dye and herbicides were applied simultaneously and evenly throughout each plot. Within each plot, three stations and water depths, as established for aqueous herbicide residue monitoring (above), were also employed for dye measurements. Dye was measured in situ using an Aquafluor® handheld fluorometer (Turner Designs, Sunnyvale, California).

Vegetation assessments

Quantitative pretreatment point intercept surveys were conducted from 26-27 July 2010 in each strip-plot using a 25-m grid to assess the plant community. Survey methods were similar to those utilized during recent projects in the Pacific Northwest (Madsen and Wersal 2008, 2009). A total of 90, 58, 76, and 82 points were surveyed in endothall, diquat, endothall + diquat, and untreated reference plots, respectively. The number of points selected for each plot was proportionally representative of plot size. The surveys were conducted by boat using GPS technology. A Dell Latitude E 6400 XFR (Round Rock, Texas) laptop computer, outfitted with a Trimble AgGPS106tm (Sunnyvale, California) GPS receiver, was

used to navigate to each point. Survey accuracy was 1-3 m, depending on satellite reception. At each survey point, a weighted thatch rake was deployed on the bottom to determine the presence of plant species. Spatial data were recorded electronically using FarmWorks Site Mate® software (Hamilton, Indiana). The software allowed for in-field geographic and attribute data collection. Data were recorded in database templates using specific pick lists constructed exclusively for this project. Site Mate® provided an environment for displaying geographic and attribute data, and guided navigation to specific locations on the lake.

At 6 weeks after treatment (6 WAT) (7-10 September 2010) and at 52 WAT (7-10 September 2011), quantitative surveys were conducted, as for pretreatment above, in all plots to assess treatment efficacy against Eurasian watermilfoil and curlyleaf pondweed, and to assess any impacts to the non-target native plant community. For each treatment, the presence of plant species was averaged over all points sampled and multiplied by 100. Changes in the occurrence of plant species between the pretreatment and 6 and 52 WAT surveys were determined for each treatment using the McNemars test (Stokes et al. 2000, Wersal et al. 2010). The McNemars test analyzes for changes in the correlated proportion within sample sites over time, where collected samples are not independent. The test is not meant to be a mean comparison test, as only presence/absence data were collected in each small plot. Species richness was calculated for each point. Means were calculated for total richness, non-native richness, and native richness and are reported as the average number per point. Species richness data were subjected to a paired t-test. All analyses were conducted using SAS® analytical software (Cary, North Carolina), at a $p < 0.05$ level of significance.

4 Results and Discussion

Aqueous herbicide residues

Endothall-treated plots. Water temperatures were essentially isothermal and ranged from 21 to 24 °C in all plots at the time of treatment. Mean endothall residues in Plots 6 and 11 (treated with endothall alone) indicated that overall herbicide concentrations were distributed throughout the water column (Table 3). Concentrations increased over time in the bottom of Plot 11, with the greatest concentration found at the last sampling period (215 ± 136 µg ai/L at 7.5 HAT). Conversely, in Plot 6, the greatest concentrations were found 1 to 4.5 HAT (90 ± 8 to 175 ± 44 µg ai/L). Endothall concentrations in both Plots 6 and 11 were more than 90% below the target concentration of 3000 µg ai/L.

Table 3. Endothall concentrations (µg ai/L) at the top, middle, and bottom of the water column in Plots 6 and 11 (treated with endothall alone) of Noxon Rapids Reservoir, MT, 2 August 2010. Concentrations are mean ±1 SE of three stations located in the plot. Target concentration was 3000 µg ai/L.

Plot 6					Plot 11			
HAT	Top	Middle	Bottom		HAT	Top	Middle	Bottom
1	110 ± 34	90 ± 8	147 ± 16		0	1 ± 1	ND	2 ± 2
3	175 ± 44	144 ± 33	127 ± 54		1	3 ± 1	3 ± 1	2 ± 0
4.5	99 ± 89	134 ± 75	115 ± 40		3	5 ± 2	4 ± 3	7 ± 4
6	67 ± 32	84 ± 58	76 ± 74		4.5	1 ± 1	70 ± 64	19 ± 14
7.5	15 ± 5	14 ± 8	35 ± 28		6	1 ± 1	11 ± 8	110 ± 84
9	31 ± 26	21 ± 16	43 ± 30		7.5	2 ± 1	3 ± 2	215 ± 136

Mean endothall residues (± 1 SE) in Plots 4 and 8 (treated with endothall+ diquat) indicated that the greatest herbicide concentrations were found in the lower half of the water column through 8 HAT (Table 4). Nonetheless, endothall concentrations were more than 75% below the target concentration of 1500 µg ai/L in these plots. Highest endothall concentrations in Plot 4 were 63 ± 25 µg ai/L in the middle depth zone and 129 ± 72 µg ai/L in the bottom depth zone. Highest endothall concentrations in Plot 8 were 214 ± 38 µg ai/L in the middle depth zone and 368 ± 185 µg ai/L in the bottom depth zone.

Table 4. Endothall concentrations (µg ai/L) at the top, middle, and bottom of the water column in Plots 4 and 8 (treated with endothall+diquat), Noxon Rapids Reservoir, MT, 28 July 2010. Concentrations are mean ±1 SE of three stations located in the plot. Target concentration of endothall was 1500 µg ai/L.

Plot 4					Plot 8			
HAT	Top	Middle	Bottom		HAT	Top	Middle	Bottom
0	1 ± 1	4 ± 4	ND		0	71 ± 70	95 ± 94	368 ± 185
1	18 ± 13	16 ± 9	62 ± 53		1	75 ± 38	68 ± 34	158 ± 90
2	5 ± 4	15 ± 8	129 ± 72		2	118 ± 106	214 ± 38	187 ± 79
3	4 ± 4	7 ± 7	51 ± 33		3	35 ± 28	88 ± 79	95 ± 81
4	54 ± 27	63 ± 25	26 ± 17		4	41 ± 37	54 ± 50	38 ± 34
					6	45 ± 29	173 ± 149	200 ± 108
					8	11 ± 7	116 ± 103	148 ± 75

These low herbicide residues may be attributed to dilution of treated water via the large fringe area of untreated water associated with the small plot size in this study. Rapid herbicide dissipation in small plots on large water bodies is quite typical. For example, dissipation of endothall in 0.2-ha plots in Wisconsin lakes treated at 3000 µg ai/L was also rapid, with calculated half-lives occurring in 3 hr (authors' unpublished data). In addition to plot size, reservoir discharge patterns can also be a factor in dilution of treated waters. In 2009, residues measured in 8-acre blocks (plots) treated with endothall in Noxon Rapids Reservoir showed whole-plot dissipation half-lives ranging from 18 to 32 hr (Getsinger et al. 2013). The 18-hr half-life occurred when reservoir discharges were 425-565 cms (15,000 – 20,000 cfs) applied from 1000–1230 hr, similar to the discharges occurring in this small-plot study, when strips were treated between 0730 and 1000 hr (Table 2). The 32-hr half-life occurred when reservoir discharges were almost nil (application from 0200–0630 hr). To maximize herbicide contact time around target plants in larger reservoirs, timing of applications should coincide with minimal reservoir discharge patterns whenever possible. In addition, more rigorous water sampling regimes within small plots (e.g., more stations, depth zones, and events) may decrease data variability and provide a better characterization of water exchange processes and herbicide dissipation.

Without the influence of water exchange processes, endothall dissipation is driven by microbial degradation and cool water temperatures. Aqueous concentrations in whole-lake treatments, where water exchange is minimal, can extend for up to 3 to 5 weeks in water temperatures less than 20 °C (Mudge and Theel 2011). In a North Carolina whole-pond treatment,

2000 µg ai/L endothall decreased linearly over time, with 1000 µg ai/L measured 14 days post treatment and 0 µg ai/L measured 26 days post treatment (Langeland and Warner 1986). Static laboratory flask studies have shown that half-lives of endothall range from 8.5 to 10 days (Reynolds 1992, Reinert et al. 1986; cited in Sprecher et al. 2002).

Diquat-treated plots. Water temperatures were essentially isothermal and ranged from 21 to 24 °C in all plots at the time of treatment. Mean diquat residues (± 1 SE) in Plot 20 indicated that the herbicide was greater in the mid- and bottom depth zones through 1.5 HAT (Table 5). A more even distribution of diquat residues in the water column was measured at 3 HAT. The greatest diquat concentrations in this plot were found immediately after treatment and ranged from 84 ± 39 ug ai/L to 126 ± 123 µg ai/L. These concentrations are 23 to 34% of the target concentration of 370 µg ai/L. Concentrations substantially decreased by 1.5 HAT, with concentrations just above the detection limit (5 µg ai/L) by 3 HAT.

Table 5. Diquat concentrations (µg ai/L) at the top, middle and bottom of the water column in Plots 20 and 22 of Noxon Rapids Reservoir, MT, 30 July 2010. Concentrations are mean ±1 SE of three stations located in the plot. Target concentrations were 370 µg ai/L.

Plot 20					Plot 22			
HAT	Top	Middle	Bottom		HAT	Top	Middle	Bottom
0	84 ± 39	151 ± 87	126 ± 123		0	ND	ND	ND
1.5	25 ± 10	53 ± 27	66 ± 20		1.5	ND	133 ± 133	ND
3	18 ± 7	14 ± 5	4 ± 4		3	95 ± 8	77 ± 39	6 ± 6
4.5	6 ± 1	7 ± 2	5 ± 3		5	80 ± 41	295 ± 206	25 ± 25
6	11 ± 6	8 ± 3	5 ± 5		6.5	104 ± 28	22 ± 22	31 ± 31
7.5	9 ± 4	12 ± 6	10 ± 7		8	101 ± 19	81 ± 46	45 ± 28
					9.5	64 ± 24	45 ± 23	96 ± 69

Contrary to Plot 20, residues measured in Plot 22 showed that the herbicide was not detected until 1.5 HAT, and found in the mid-depth zone (Table 5). However, some level of diquat was maintained in the water column through 9.5 HAT. The highest concentrations were in the top and middle of the water column, with 295 ± 206 µg ai/L found at 5 HAT. Although this concentration represents 80% of the target (370 µg ai/L), concentrations ranged from 6 to 36% of the target throughout the plot for the length of the sampling period. Distribution of diquat residues in Plot 22 indicated that this plot exhibited better water column mixing than Plot 20.

Like endothall, diquat residues were less than target concentrations, likely due to dilution from untreated water in the large fringe area associated with the small plot size used in this study, and reservoir discharge patterns at the time of treatments. Dilution due to large treatment area depths accounted for low diquat concentrations in a whole-lake treatment of Battle Ground Lake, Washington (Parsons et al. 2004). Despite a target concentration of 370 µg ai/L, diquat concentrations ranged from 0.7 to 90 µg ai/L 4 HAT in Battle Ground Lake. It is well known that degradation of diquat (a strong cation) occurs due to rapid adsorption by negatively charged particles, such as suspended sediment, algae, and plant seston. It is possible that the depth of herbicide discharge using the variable depth application hoses may have been close enough to the bottom that sediment resuspension would have caused adsorption of diquat cations. Furthermore, diquat can quickly dissipate even in large treatment blocks and whole-pond applications. For example, diquat decreased by 50 to 80% within 5 hr of application in a whole-pond application (Langeland and Warner 1986). High diquat rates are needed to overcome the adsorption of suspended sediment to provide effective control of aquatic plants (Poovey and Getsinger 2002, Poovey et al. 2002. The target rate of diquat applied in this study was the maximum allowed on the label (0.37 µg ai/L).

Bulk water exchange processes

Endothall-treated plots. Estimated bulk water-exchange processes in endothall-treated plots are depicted in Figures 6-9. Dye concentrations were measured at < 3.5 µg ai/L during the 8- to 9-HAT sampling periods. These values were approximately 70% below the target application rate of 10 ppb, and resembled endothall residue patterns measured in these plots (Tables 3 and 4). And, like endothall residues, higher dye levels were measured in the mid to lower portions of the water column.

Diquat-treated plots. Estimated bulk water-exchange processes in diquat-treated plots are depicted in Figures 10–13. Similar to diquat residues in Plot 20 (Table 5), dye levels in this plot were greatest in mid and bottom depth zones (Figure 10), but unlike diquat residues, dye concentrations exceeded the target application rate. In Plot 22 (Figure 12), dye levels were highest at surface and mid-depth zones, and lower in bottom waters, similar to diquat residues in that plot (Table 5). In the other diquat-treated plots (21 and 24), dye levels were greatest at the bottom and middle depth zones (Figures 11 and 13).

Figure 6. Dissipation of dye from endothall-treated Plot 6, 2 August 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

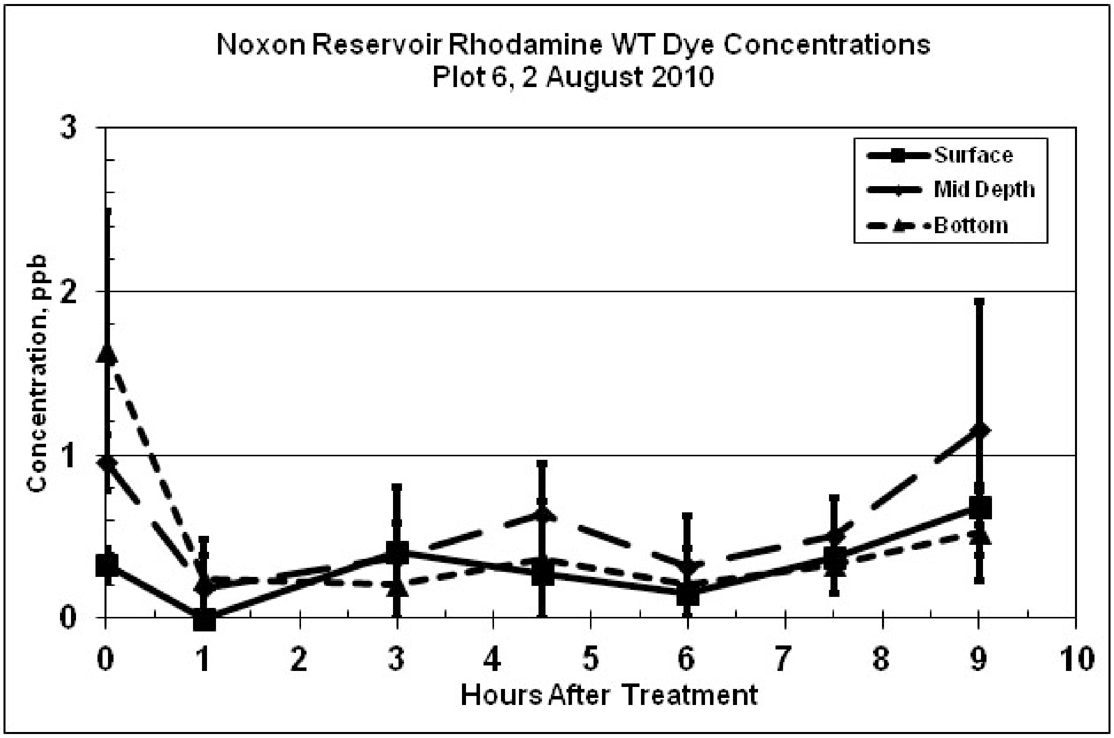


Figure 7. Dissipation of dye from endothall-treated Plot 9, 2 August 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

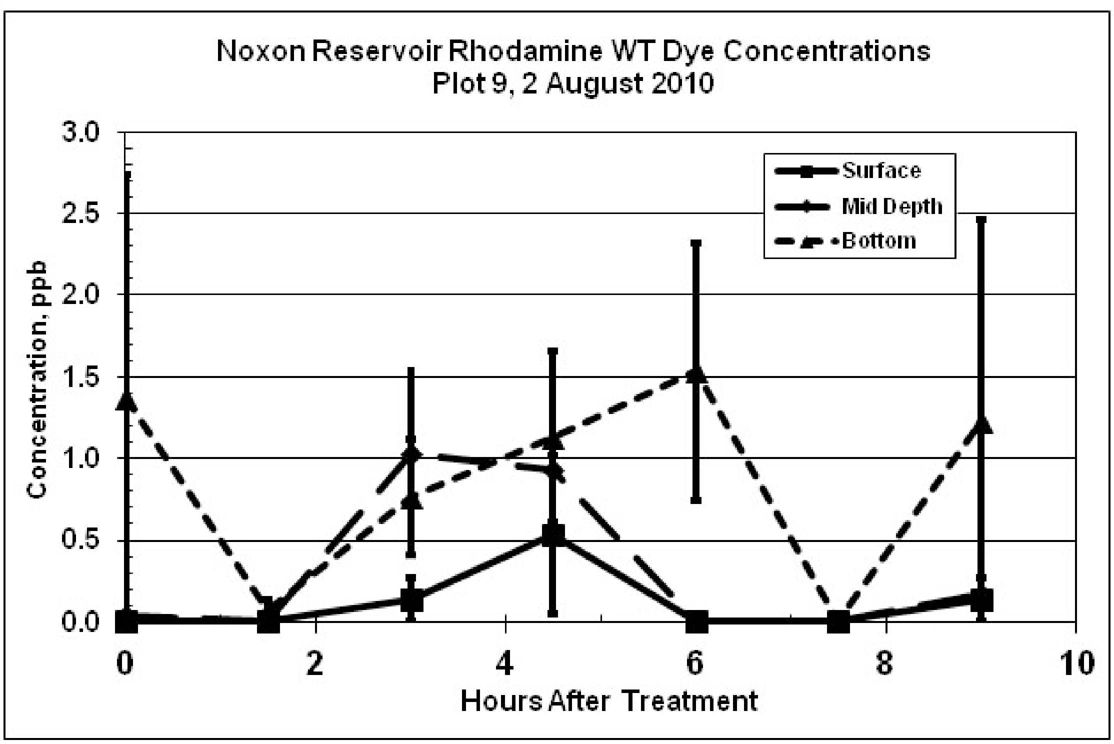


Figure 8. Dissipation of dye from endothall-treated Plot 11, 2 August 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

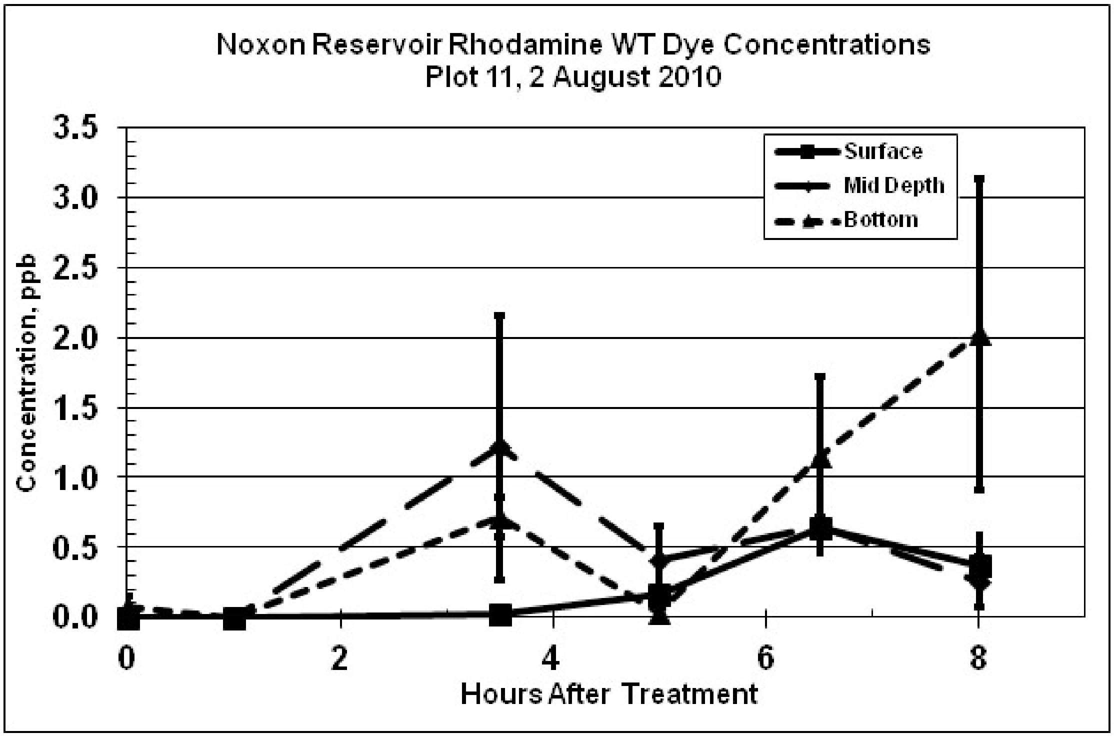


Figure 9. Dissipation of dye from endothall-treated Plot 19, 2 August 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

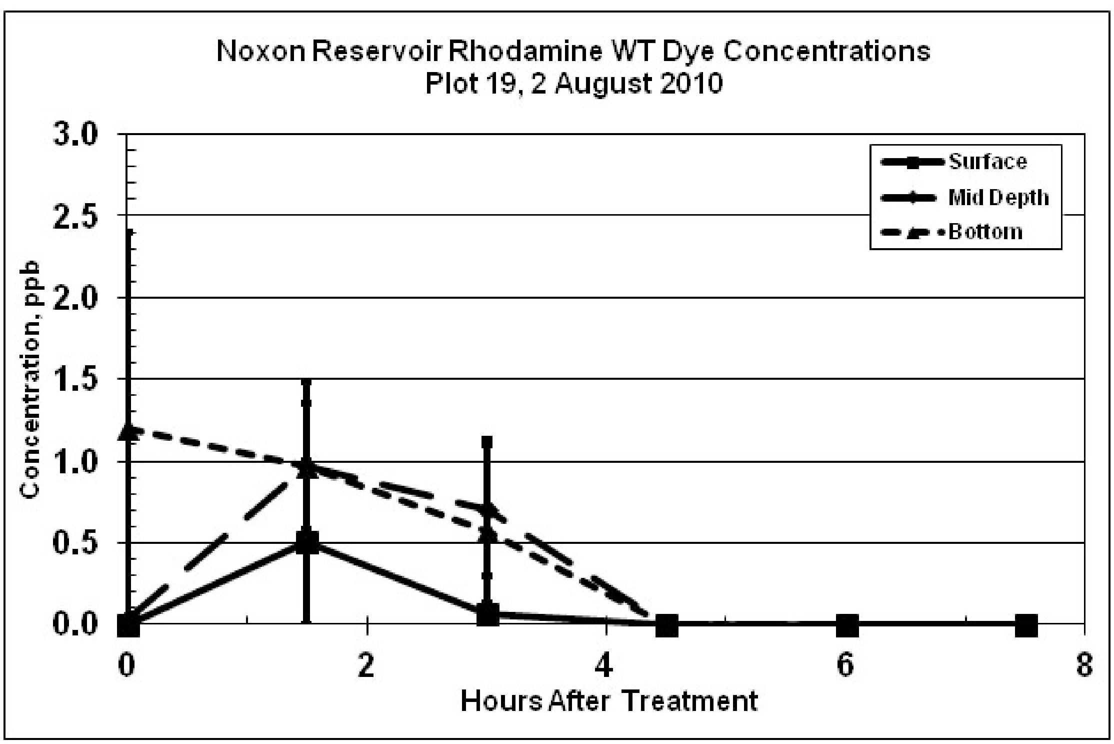


Figure 10. Dissipation of dye from diquat-treated Plot 20, 30 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

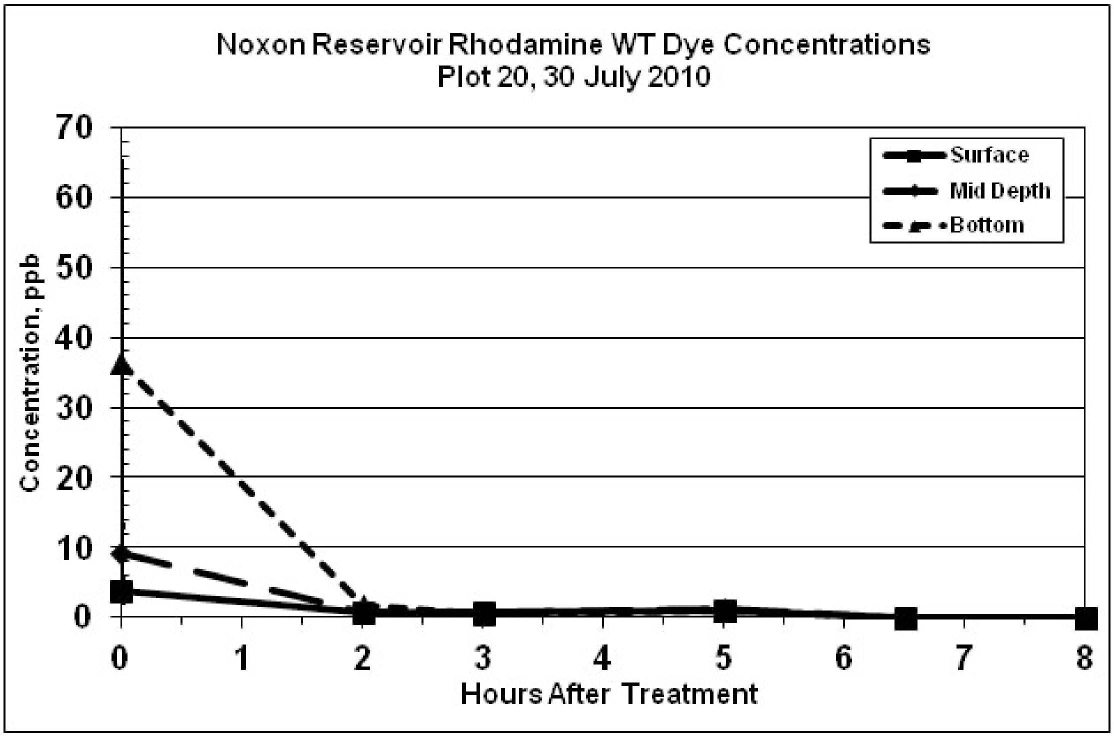


Figure 11. Dissipation of dye from diquat-treated Plot 21, 30 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

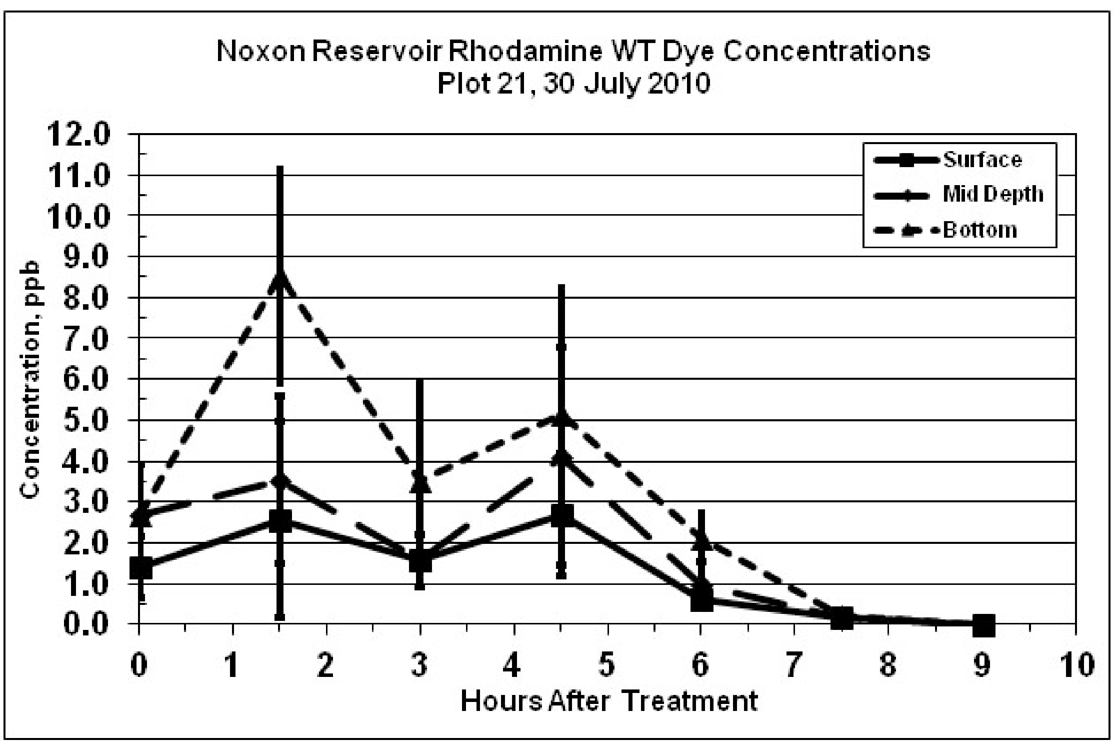


Figure 12. Dissipation of dye from diquat-treated Plot 22, 30 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

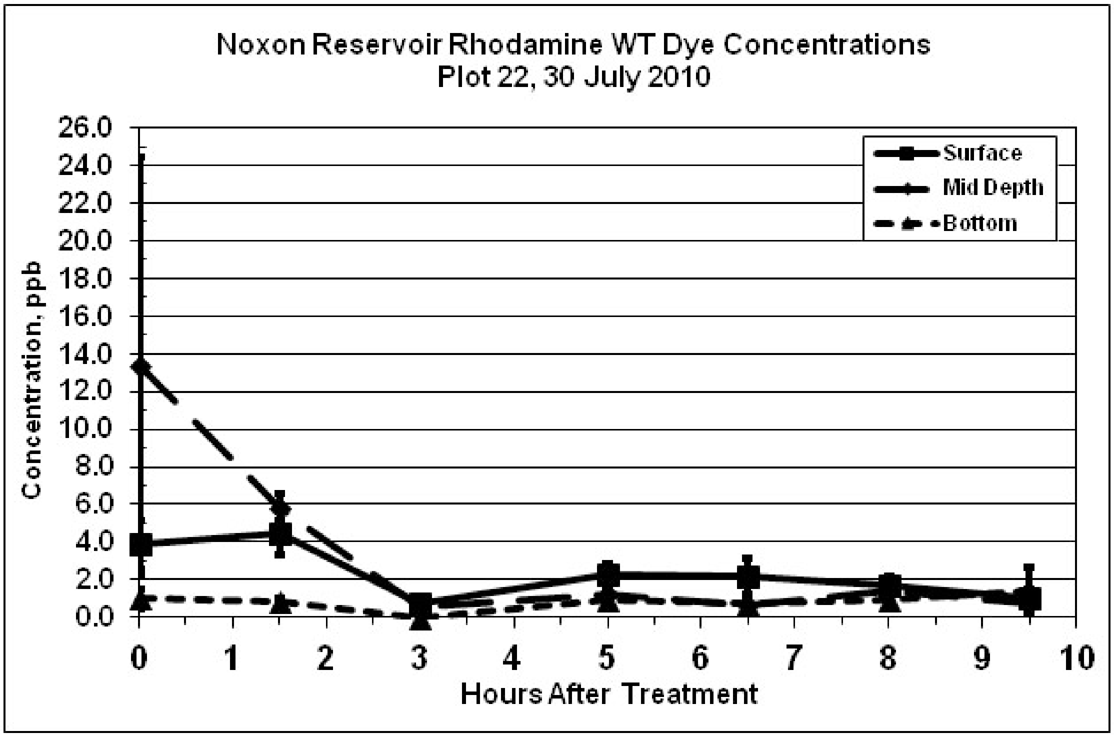
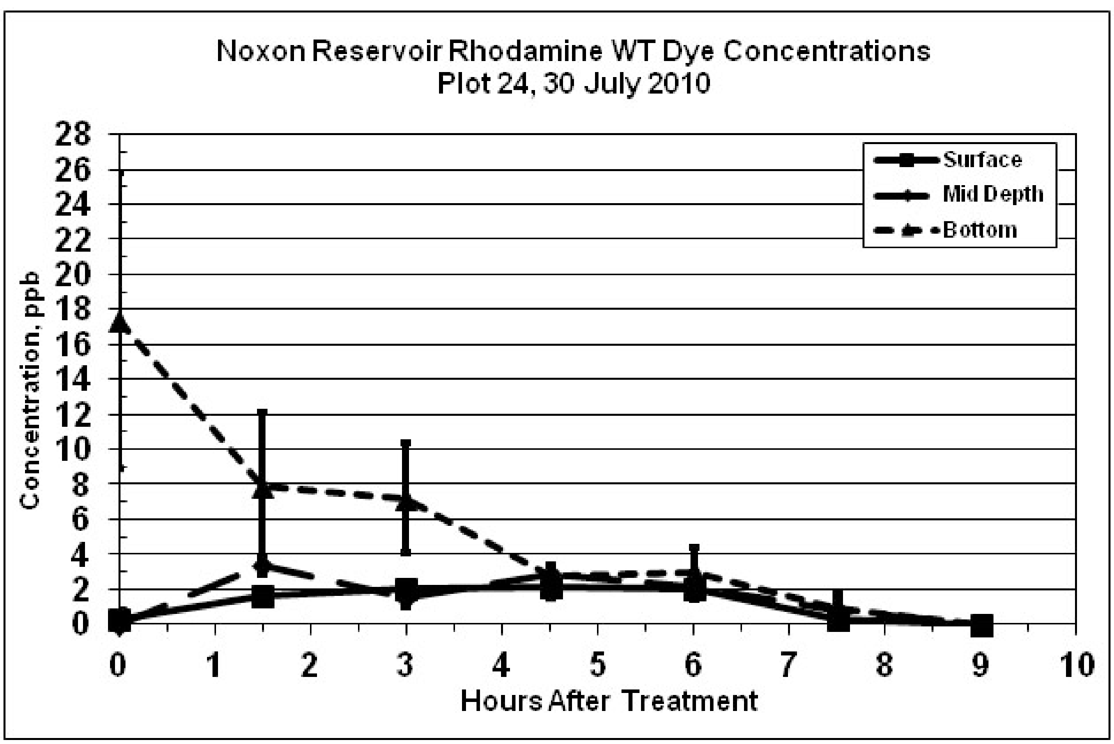


Figure 13. Dissipation of dye from diquat-treated Plot 24, 30 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).



Endothall+Diquat-treated plots. Estimated bulk water-exchange processes in endothall+diquat-treated plots are depicted in Figures 14-17. Dye concentrations were typically higher in mid and bottom depth zones. Dye concentrations in Plots 4 and 8 (Figures 15 and17) showed distribution and dissipation patterns similar to those depicted by endothall residues in the same plots (Table 4).

In general, dye distribution and dissipation patterns were similar to those indicated by herbicide residue levels. While dye levels were measured throughout the sampling period (8-9 HAT), levels were low and declined quickly in most plots, particularly after the 3-HAT sampling event. Hence, dye movement indicated that bulk water exchange processes were active during herbicide treatments, and that herbicide contact time in plant stands would be short. Highest concentrations of dye were primarily located in the mid and bottom depth zones in 10 of the 12 plots treated. This distribution pattern would be expected as a function of the variable depth delivery technique, which targeted the bottom third of the water column.

Figure 14. Dissipation of dye from endothall+diquat-treated Plot 2, 28 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

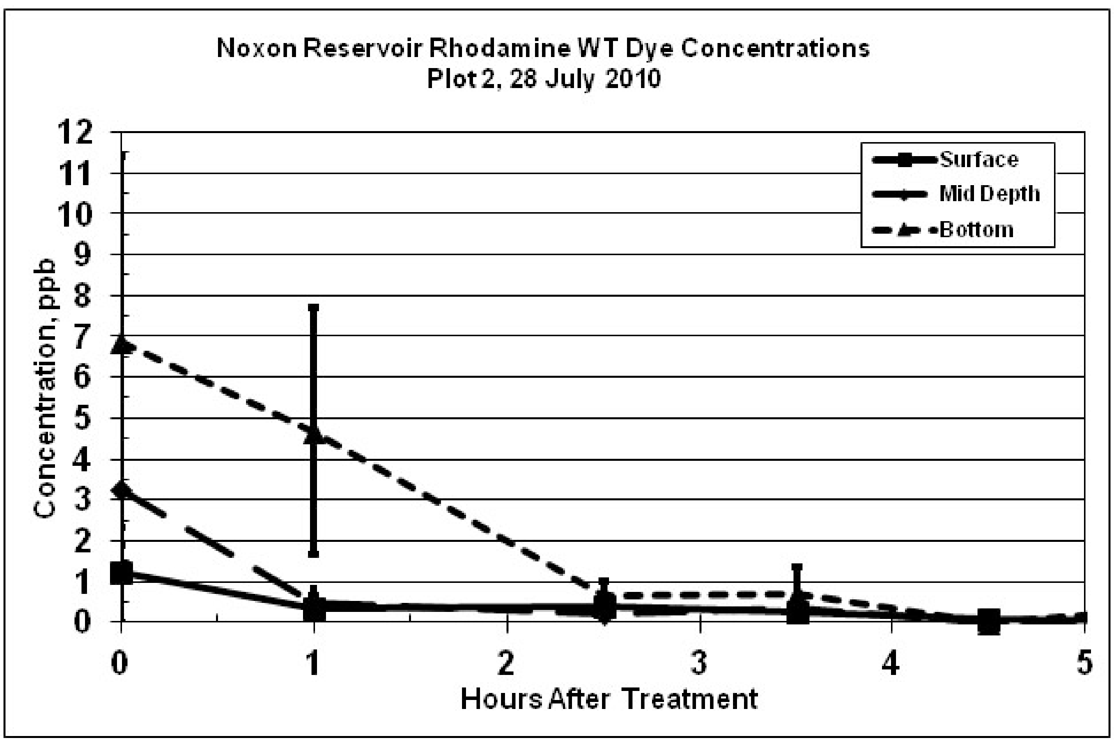


Figure 15. Dissipation of dye from endothall+diquat-treated Plot 4, 28 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

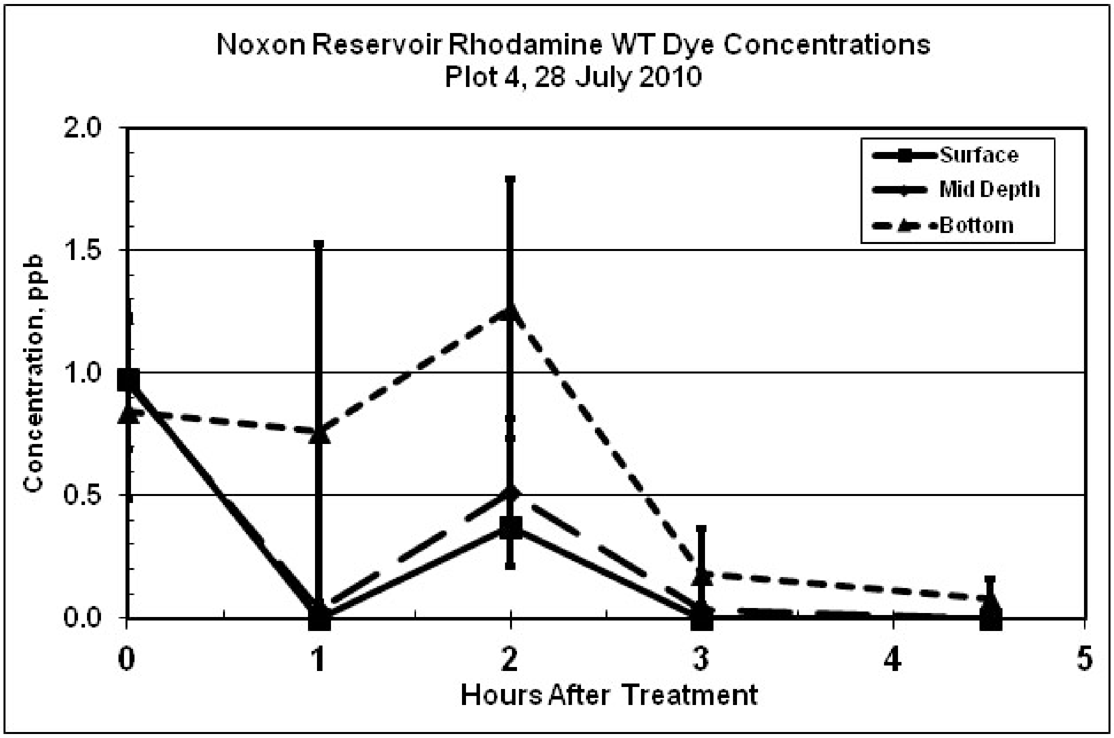


Figure 16. Dissipation of dye from endothall+diquat-treated Plot 7, 28 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).

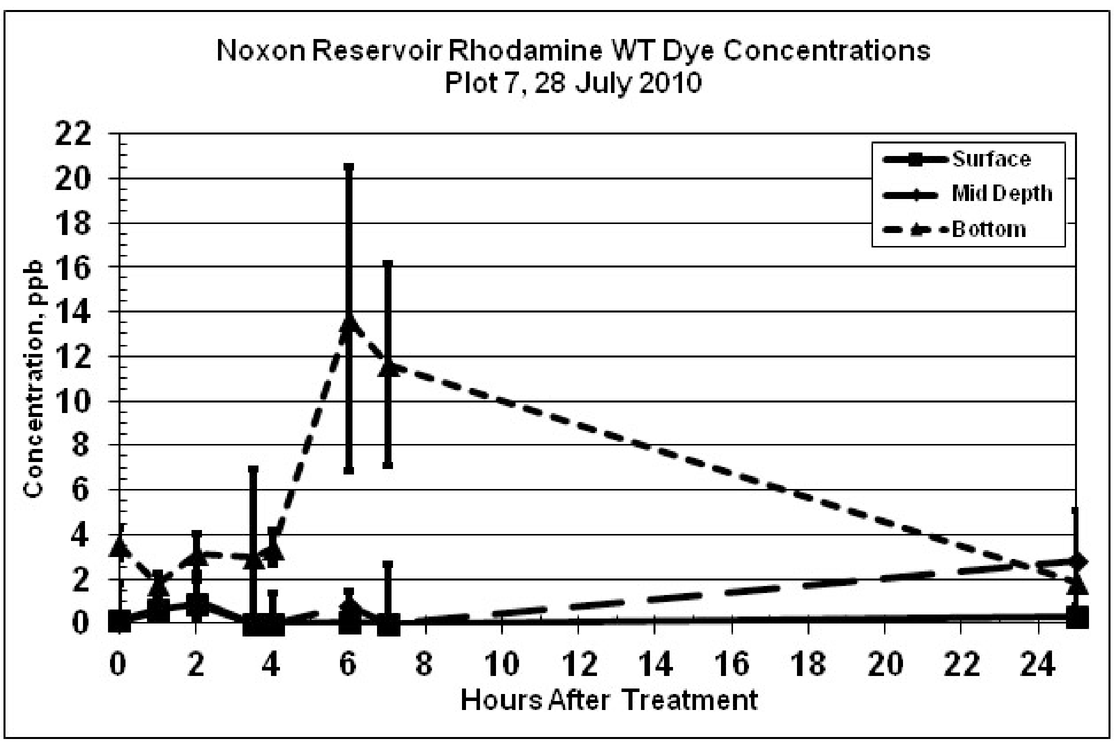
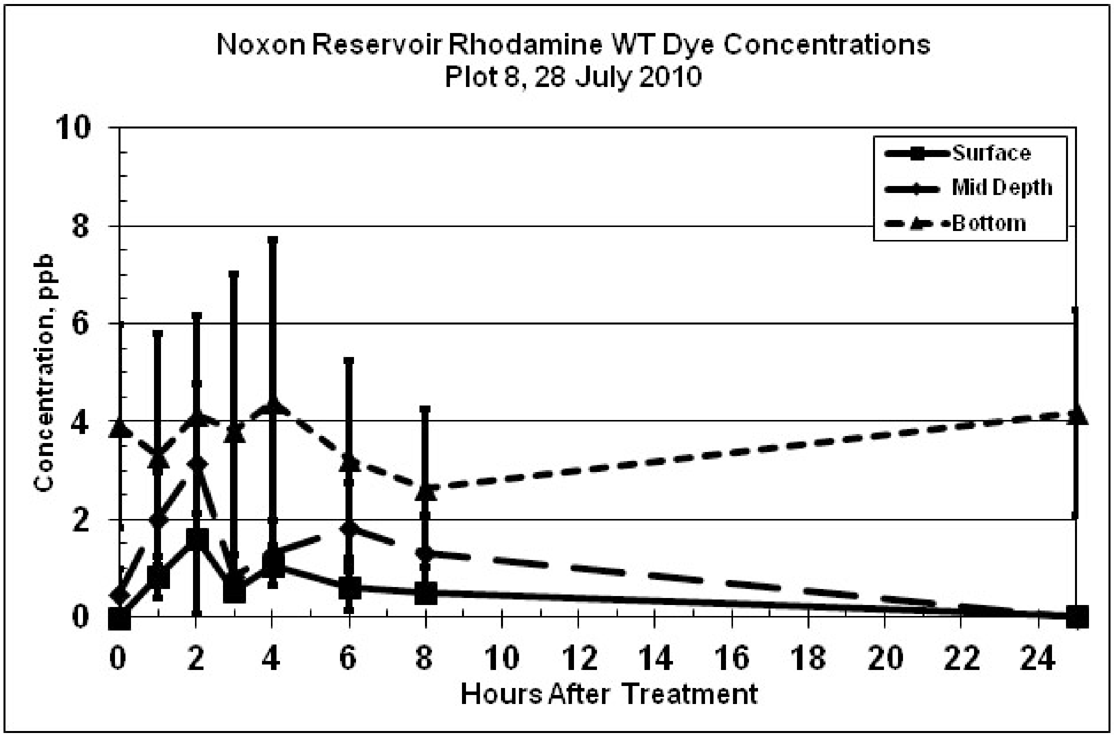


Figure 17. Dissipation of dye from endothall+diquat-treated Plot 8, 28 July 2010, Noxon Rapids Reservoir, MT. Data represent mean dye concentration (± standard error) at each sampling station (surface, mid-depth, bottom).



Vegetation assessments

Endothall-treated plots. Pre- and post-treatment vegetation assessments for endothall-treated plots are shown in Table 6. Based on percent occurrence, Eurasian watermilfoil was reduced by 52% at 6 WAT and 69% at 52 WAT compared to pretreatment levels. In addition, curlyleaf pondweed significantly declined, from 77% occurrence pretreatment to 37% occurrence 52 WAT. This level of control for both species was not unexpected considering the size, location, and rapid water-exchange characteristics of the plots. Declines in curlyleaf 6 WAT can also be attributed to natural senescence (Woolf and Madsen 2003), given the timing of the treatment and subsequent survey. Follow-up treatments will be required to further reduce the abundance of these plants in strips along the shoreline. These results verify laboratory dose/response relationships developed for endothall against Eurasian watermilfoil and curlyleaf pondweed under short exposure times (Netherland et al. 1991, 2000).

Table 6. Aquatic plant occurrence in treatment plots (n=4) after being treated with endothall in Noxon Rapids Reservoir, MT, 2010-11 (Plots 6, 9, 11, 19). Differences between sampling events were determined at a $p < 0.05$ significance level using the McNemars test. Survey data were only compared to pretreatment data († denotes a difference between 6 weeks post-treatment and pretreatment, * denotes a difference between 1 year and pretreatment). Species richness values, within a given category, sharing the same letter are not different according to a Fisher's Protected LSD test at a $p < 0.05$ significance level.

Plant Species	Common Name	Pretreatment % Occurrence	6 Weeks After Treatment % Occurrence	1 Year After Treatment % Occurrence
Butomus umbellatus L.	Flowering rush	4	1	0
Ceratophyllum demersum L.	Coontail	33	23	20*
Chara sp.	Muskgrass	12	24†	47*
Elodea canadensis Michx.	Elodea	50	48	64
Heteranthera dubia (Jacq.) Small	Water stargrass	17	6†	10
Myriophyllum sibiricum Komarov	Northern watermilfoil	54	21†	7*
Myriophyllum spicatum L.	Eurasian watermilfoil	42	20†	13*
Najas flexilis L. (Willd.) Rost & Schmidt	Slender naiad	0	0	1
Nitella sp.	Stonewort	0	6	0
Potamogeton crispus L.	Curlyleaf pondweed	77	11†	37*
Potamogeton foliosus Raf.	Leafy pondweed	8	2	13
Potamogeton illinoensis Morong	Illinois pondweed	2	6	0
Potamogeton praelongus Wulf.	Whitestem pondweed	1	1	0
Potamogeton richardsonii (Ar. Benn.) Rydb.	Clasping-leaved pondweed	22	2†	3*
Ranunculus aquatilis L.	White water-buttercup	36	27	26
Stuckenia pectinata (L.) Börner	Sago pondweed	21	3†	13
Total Species Richness (Avg. Number Point^{-1})		3.8a	2.0b	2.5c
Non-native Richness (Avg. Number Point^{-1})		1.2a	0.3b	0.5b
Native Richness (Avg. Number Point^{-1})		2.5a	1.7b	2.0b

- Total species richness (number of species per point) showed a significant decline from 3.8 to 2.5 after endothall treatment, largely due to reductions in Eurasian watermilfoil, curlyleaf pondweed (the two targeted invasive weeds), and the native species northern watermilfoil (87% reduction), clasping-leaved pondweed (86% reduction), and coontail (39% reduction). Although coontail occurrence pretreatment was similar to occurrence 6 WAT, it decreased at 52 WAT. Coontail is reported as being moderately sensitive to endothall, where concentrations of >2 µg ai/L negatively affect growth and biomass (Skogerboe and Getsinger 2002). Conversely, water stargrass and sago pondweed were significantly reduced 6 WAT, but by 52 WAT the occurrence of these species returned to pretreatment levels. These species are considered more tolerant of endothall (Skogerboe and Getsinger 2002, Skogerboe et al. 2008, Slade et al. 2008). Other native species, such as elodea, leafy pondweed, and white water-buttercup, were not significantly affected by endothall applications. Chara increased two-fold 6 WAT and four-fold 52 WAT. Chara is an important pioneer species that colonizes quickly after herbicide treatments (Wade 1990) and has been reported to significantly increase after endothall applications (Parsons et al. 2004).

Various levels of phytoxicity should be expected against some native species using contact herbicides; however, reductions in these species can also be driven by natural cycles and seasonal ambient conditions (Getsinger et al. 2013). For example, reductions in these species also occurred in reference plots that were not treated with herbicides (Table 9).

Diquat-treated plots. Pre- and post-treatment vegetation assessments for diquat-treated plots are shown in Table 7. Based on percent occurrence, Eurasian watermilfoil was reduced by 57% at 6 WAT and by 66% at 52 WAT. Similarly, the presence of Eurasian watermilfoil was reduced by 70% in Lake Pend Oreille, Idaho, which is another run of the river reservoir on the Lower Clarke Fork River, roughly 70 miles downstream from Noxon Rapids Reservoir (Madsen and Wersal 2008). Given the treated water volumes, small plot sizes, and bulk water exchange processes in the lake, this level of control would be considered acceptable relative to the calculated half-lives of the herbicides in the treated plots.

Table 7. Aquatic plant occurrence in treatment plots (n=4) after being treated with diquat in Noxon Rapids Reservoir, MT, 2010-11 (Plots 20, 21, 22, 24). Differences between sampling events were determined at a $p < 0.05$ significance level using the McNemars test. Comparisons in survey data were only made to pretreatment data († denotes a difference between 6 weeks post-treatment and pretreatment, * denotes a difference between 1 year and pretreatment). Species richness values, within a given category, sharing the same letter are not different according to a Fisher's Protected LSD test at a $p < 0.05$ significance level.

Plant Species	Common Name	Pretreatment % Occurrence	6 Weeks After Treatment % Occurrence	1 Year After Treatment % Occurrence
Butomus umbellatus L.	Flowering rush	2	0	2
Ceratophyllum demersum L.	Coontail	26	27	26
Chara sp.	Muskgrass	9	12	19
Elodea canadensis Michx.	Elodea	37	18†	39
Heteranthera dubia (Jacq.) Small	Water stargrass	11	40†	31*
Myriophyllum sibiricum Komarov	Northern watermilfoil	41	42	14*
Myriophyllum spicatum L.	Eurasian watermilfoil	70	30†	24*
Najas flexilis L. (Willd.) Rost & Schmidt	Slender naiad	0	0	2
Nitella sp.	Stonewort	0	2	0
Potamogeton crispus L.	Curlyleaf pondweed	60	9†	36*
Potamogeton foliosus Raf.	Leafy pondweed	5	0	34*
Potamogeton illinoensis Morong.	Illinois pondweed	0	2	0
Potamogeton richardsonii (Ar. Benn.) Rydb.	Clasping-leaved pondweed	25	23	9*
Ranunculus aquatilis L.	White water-buttercup	44	9†	12*
Stuckenia pectinata (L.) Börner	Sago pondweed	23	5†	9*
Total Species Richness (Avg. Number Point^{-1})		3.4a	2.1b	2.5b
Non-native Richness (Avg. Number Point^{-1})		1.2a	0.3b	0.6b
Native Richness (Avg. Number Point^{-1})		2.1a	1.7a	1.9a

Curlyleaf pondweed decreased from 60% occurrence at pretreatment to 36% occurrence 52 WAT, a 40% reduction in the presence of curlyleaf pondweed. Again, the phenology of curlyleaf pondweed should be considered in future applications to improve control of this target weed. Similar to endothall, diquat is effective at controlling both Eurasian

watermilfoil and curlyleaf pondweed under short exposure times (Netherland et al. 2000, Skogerboe et al. 2006).

Total species richness significantly decreased from 3.4 to 2.5 species per point. This was likely due to reductions in the invasive Eurasian watermilfoil and curlyleaf pondweed, as non-native species richness also showed a significant decline. Native species richness was not affected by the diquat treatment. This was probably due to the expansion of water stargrass and leafy pondweed populations. Occurrence of other native species, including northern watermilfoil, clasping-leaved pondweed, sago pondweed, and white water-buttercup significantly decreased by 66, 64, 61, and 73%, respectively; while coontail and chara were not significantly impacted by the diquat applications. It is noteworthy that one pondweed species (leafy pondweed) substantially increased, while clasping-leaf and sago pondweed decreased. A plausible explanation for this may be the fact that leafy pondweed is a small seeded annual. Removal of Eurasian watermilfoil and other species from the plot allowed for greater seed germination and subsequent growth of leafy pondweed by 52 weeks post treatment. Although diquat is generally considered a broad-spectrum herbicide, differential susceptibility among pondweeds has been reported (Skogerboe et al. 2006).

As with endothall, various levels of phytoxicity against some native species should be expected using contact herbicides; however, reductions in these species can also be driven by natural cycles and seasonal ambient conditions. It should also be noted that species-selective properties can differ between contact herbicides, such as endothall and diquat.

Endothall+diquat-treated plots. Pre- and post-treatment vegetation assessments for endothall+treated plots are shown in Table 8. Based on percent occurrence, the combination of endothall+diquat reduced Eurasian watermilfoil by 64% at 6 WAT and by 59% at 52 WAT. Likewise, curlyleaf pondweed declined by 59%, with 61% occurrence pretreatment and 25% at 52 WAT.

Total species richness decreased after the diquat+endothall treatments by 52 WAT. In addition to the targeted weed species, Eurasian watermilfoil and curlyleaf pondweed, many native species also significantly declined, including elodea (60% reduction), northern watermilfoil (93% reduction), white water-buttercup (100% reduction), and all of the pondweeds except

leafy pondweed. The presence of coontail and water stargrass was constant through 52 WAT, while chara and leafy pondweed increased. Native species richness declined from 2.6 species per point during pretreatment surveys to 1.5 and 1.2 species per point at 6 and 52 WAT, respectively. It is important to note that even though native species richness declined significantly, some species survived to provide submersed aquatic habitat.

Table 8. Aquatic plant occurrence in treatment plots (n=4) after being treated with diquat+endothall in Noxon Rapids Reservoir, MT, 2010-11 (Plots 2, 4, 7, 8). Differences between sampling events were determined at a $p < 0.05$ significance level using the McNemars test. Comparisons in survey data were only made to pretreatment data († denotes a difference between 6 weeks post-treatment and pretreatment, * denotes a difference between 1 year and pretreatment). Species richness values, within a given category, sharing the same letter are not different according to a Fisher's Protected LSD test at a $p < 0.05$ significance level.

Plant Species	Common Name	Pretreatment % Occurrence	6 Weeks After Treatment % Occurrence	1 Year After Treatment % Occurrence
Butomus umbellatus L.	Flowering rush	1	0	1
Ceratophyllum demersum L.	Coontail	13	8	5
Chara sp.	Muskgrass	36	53†	52*
Elodea canadensis Michx.	Elodea	47	11†	19*
Heteranthera dubia (Jacq.) Small	Water stargrass	22	20	23
Myriophyllum sibiricum Komarov	Northern watermilfoil	55	22†	4*
Myriophyllum spicatum L.	Eurasian watermilfoil	22	8†	9*
Najas flexilis L. (Willd.) Rost & Schmidt	Slender naiad	0	0	3
Nitella sp.	Stonewort	0	14†	0
Potamogeton crispus L.	Curlyleaf pondweed	61	3†	25*
Potamogeton foliosus Raf.	Leafy pondweed	0	3	13*
Potamogeton illinoensis Morong	Illinois pondweed	12	3†	0*
Potamogeton richardsonii (Ar. Benn.) Rydb.	Clasping-leaved pondweed	40	9†	3*
Ranunculus aquatilis L.	White water-buttercup	24	3†	0*
Stuckenia pectinata (L.) Börner	Sago pondweed	20	0†	5*
Total Species Richness (Avg. Number Point^{-1})		3.4a	1.5b	1.5b
Non-native Richness (Avg. Number Point^{-1})		0.8a	0.1b	0.3c
Native Richness (Avg. Number Point^{-1})		2.6a	1.5b	1.2b

Untreated reference plots. Pre- and post-treatment vegetation assessments for untreated reference plots are shown in Table 9. The presence of Eurasian watermilfoil and curlyleaf pondweed remained unchanged at 52 WAT. The decrease in curlyleaf pondweed (82% at 6 WAT) represents its natural senescence in late summer (Woolf and Madsen 2003, Wersal et al. 2006). Since Eurasian watermilfoil and curlyleaf pondweed maintained consistent population levels in the reference, it can be concluded that reduction of these plants in treatment plots was due to the herbicide applications. Reference plots were included in the study to indicate what would happen in a "no management" scenario. If the target species remained constant, or increased through time, then it can be reasonably assumed that the herbicides had an effect on the treatment plots.

Total species richness declined at 6 WAT due to reductions in the presence of curlyleaf pondweed, but at 52 WAT total species richness was similar to pretreatment. Native species richness was also maintained, indicating that declines in northern watermilfoil and white water-buttercup were offset by increases in coontail, elodea, and leafy pondweed. These were the same species that fluctuated in the treatment plots, suggesting that these populations were affected by seasonal ambient factors other than the herbicide treatments.

Table 9. Aquatic plant occurrence in untreated reference plots (n=4) in Noxon Rapids Reservoir, MT, 2010-11 (Plots 12, 13, 15, 16). Differences between sampling events were determined at a $p < 0.05$ significance level using the McNemars test. Comparisons in survey data were only made to pretreatment data († denotes a difference between 6 weeks post-treatment and pretreatment, * denotes a difference between 1 year and pretreatment). Species richness values, within a given category, sharing the same letter are not different according to a Fisher's Protected LSD test at a $p < 0.05$ significance level.

Plant Species	Common Name	Pretreatment % Occurrence	6 Weeks After Treatment % Occurrence	1 Year After Treatment % Occurrence
Butomus umbellatus L.	Flowering rush	9	1†	5
Ceratophyllum demersum L.	Coontail	35	59†	62*
Chara sp.	Muskgrass	5	2	6
Elodea canadensis Michx.	Elodea	33	39	55*
Heteranthera dubia (Jacq.) Small	Water stargrass	11	35†	33*
Myriophyllum sibiricum Komarov	Northern watermilfoil	50	56	15*
Myriophyllum spicatum L.	Eurasian watermilfoil	51	45	38
Nitella sp.	Stonewort	5	0	0
Potamogeton crispus L.	Curlyleaf pondweed	65	12†	52
Potamogeton foliosus Raf.	Leafy pondweed	15	10	33*
Potamogeton illinoensis Morong	Illinois pondweed	1	0	1
Potamogeton praelongus Wulf.	Whitestem pondweed	5	0	2
Potamogeton richardsonii (Ar. Benn.) Rydb.	Clasping-leaved pondweed	21	20	15
Ranunculus aquatilis L.	White water-buttercup	48	30†	18*
Stuckenia pectinata (L.) Börner	Sago pondweed	27	9†	17
Vallisneria americana Mich.	Wildcelery	0	1	0
Total Species Richness (Avg. Number Point^{-1})		3.8a	3.2b	3.6ab
Non-native Richness (Avg. Number Point^{-1})		1.3a	0.6b	0.9c
Native Richness (Avg. Number Point^{-1})		2.6a	2.6a	2.6a

5 Conclusions and Recommendations

Conclusions

The following conclusions were reached as a result of the evaluations documented in this report:

- When applied to small, narrow shoreline strips of plants in Noxon Reservoir, the contact herbicides endothall and diquat applied alone or in combination can provide significant reductions in the invasive species Eurasian watermilfoil (59-69%) and curlyleaf pondweed (40-60%), through 1 year post treatment. Additional herbicide treatments will be required to improve these levels of control.
- Various levels of phytoxicity against some native species should be expected when using contact herbicides; however, reductions in these species can also be driven by natural cycles and seasonal ambient conditions. For example, reductions in these species also occurred in reference plots that were not treated with herbicides.
- Since these treatments were conducted near the period of natural decline in curlyleaf pondweed biomass, caution should be used when interpreting herbicide efficacy against this plant in this application window. Because this species declines naturally in late summer, it would be difficult to determine whether the herbicide treatments alone were responsible for the large decline in curlyleaf pondweed occurrence by 6 WAT, measured in both herbicide-treated and untreated reference plots. In addition, the 52 WAT control of curlyleaf pondweed may be confounded with the annual growth variability of this plant.
- Despite being regarded as broad-spectrum herbicides, endothall and diquat can provide some degree of species-selective control. While shifts in native plant populations will occur following a treatment using these products, these changes may not differ greatly from naturally occurring seasonal shifts in untreated areas.
- Since water exchange dynamics are complex in small plots, more intense water sampling events and locations will be required to reduce variability and inconsistency of data, and to develop a better understanding of herbicide contact time and water exchange processes.
- Liquid herbicides can be targeted and delivered to bottom zones of treatment areas using a variable-depth application technique.

However, there is some inconsistency in delivery to bottom depth zones that may result in variability in control of target plants.

Results of this study show some success in treating target weeds in narrow shoreline strips. However, additional efforts to link water exchange patterns to the refinement of herbicide application techniques and treatment windows will be necessary to improve selective control of target invasive plants in Noxon Rapids and similar reservoirs.

Recommendations

The following recommendations are made based on the evaluations documented in this report:

- Additional evaluations should be conducted to determine if repeated applications of endothall and diquat can further reduce Eurasian watermilfoil and curlyleaf pondweed abundance, while minimizing injury to, and reduction of, native plants. These evaluations should include a wider range of herbicide application rates to determine the lowest rates required for optimal species-selective control of target plants.
- Since water exchange dynamics are complex in small plots, more information is needed on water column mixing and dissipation processes, as related to herbicide contact times in these treatment settings.
- The species-selective properties of diquat should be evaluated in field settings to determine appropriate application rates and treatment timing.
- The newly registered contact herbicide, flumioxazin, should be evaluated for selective control of Eurasian watermilfoil and curlyleaf pondweed in shoreline strips in the reservoir.
- A long-term strategy for controlling curlyleaf pondweed should be developed based on phenological events specific to Noxon Rapids Reservoir.

References

Clean Lakes, Inc. 2010. *2010 Eurasian watermilfoil/curlyleaf pondweed, Research Project Phase 2, Strip treatments-aquatic herbicide applications, Noxon Rapids Reservoir, Sanders County, Montana*. www.Cleanlake.com.

Getsinger, K. D., J. D. Madsen, R. M. Wersal, J. G. Skogerboe, J. J. Nawrocki, R. J. Richardson, and M. R. Sternberg. 2013. *Selective control of Eurasian watermilfoil and curlyleaf pondweed in Noxon Rapids Reservoir, Montana: Aquatic herbicide evaluations 2009-2010*. ERDC/EL TR-13-5. Vicksburg, MS: US Army Engineer Research and Development Center.

Langeland, K. A., and J. P. Warner. 1986. Persistence of diquat, endothall, and fluridone in ponds. *J. Aquat. Plant Manage*. 24:43-46.

Madsen, J. D., and J. C. Cheshier. 2009. *Eurasian watermilfoil survey of three reservoirs in the Lower Clark Fork River, Montana: I. Results of the field vegetation survey*. Geosystems Research Institute Report 5033.

Madsen, J. D., and R. M. Wersal. 2008. *Assessment of Eurasian watermilfoil (Myriophyllum spicatum L.) populations in Lake Pend Oreille, Idaho for 2007*. GeoResources Institute Report 5028. http://www.gri.msstate.edu/publications/docs/2008/04/3737GRI_Report_5028.pdf

Madsen, J. D., and R. M. Wersal. 2009. *Aquatic plant community and Eurasian watermilfoil (Myriophyllum spicatum L.) management assessment in Lake Pend Oreille, Idaho for 2008*. Geosystems Research Institute Report 5032. http://www.gri.msstate.edu/publications/docs/2009/03/5706GRI_5032_2009.pdf

Madsen, J. D., R. M. Wersal, K. D. Getsinger, and J. G. Skogerboe. 2010. *Combinations of endothall with 2,4-D and triclopyr for Eurasian watermilfoil control*. APCRP Technical Notes Collection. ERDC/TN APCRP-CC-14. Vicksburg, MS: US Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/aqua/

Mudge, C. R., and H. J. Theel. 2011. *Endothall concentration exposure time evaluation against Eurasian watermilfoil at a lower water temperature*. APCRP Technical Notes Collection. ERDC/TN APCRP-CC-15. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/aqua/

Munch, J. W., and W. J. Bashe. 1997. *Determination of diquat and paraquat in drinking water by liquid-solid extraction and high performance liquid chromatography with ultraviolet detection*. USEPA Method 549.2. Revision 1.0. US Department of Agriculture.

Netherland, M. D., J. D. Skogerboe, C. S. Owens, and J. D. Madsen. 2000. Influence of water temperature of the efficacy of diquat and endothall versus curlyleaf pondweed. *J. Aquat. Plant Manage.* 38: 25-32.

Netherland, M. D., W. R. Green, and K. D. Getsinger. 1991. Endothall concentration and exposure time relationships for the control of Eurasian watermilfoil and hydrilla. *J. Aquat. Plant Manage*. 29: 61-67.

Parsons, J. K., K. S. Hamel, S. L. O'Neal, and A. W. Moore. 2004. The impact of endothall on the aquatic plant community of Kress Lake, Washington. *J. Aquat. Plant Manage.* 42:109-114.

Poovey, A. G., and K. D. Getsinger. 2002. The effects of inorganic turbidity on diquat efficacy against *Egeria densa*. *J. Aquat. Plant Manage.* 40:6-10.

Poovey, A. G., J. G. Skogerboe, and C. S. Owens. 2002. Spring treatments of diquat and endothall for curlyleaf pondweed control. *J. Aquat. Plant Manage.* 40:63-67.

Reinert, K. H., J. H. Rodgers, Jr., T. J. Leslie, and M. L. Hinman. 1986. Static shake-flask biotransformation of endothall. *Water Res.* 20:255-258.

Reynolds, J. L. 1992. *Aerobic aquatic metabolism of ^{14}C-endothall dipotassium salt*. Elf Atochem North America, Inc., Study No. BR-91-46. MRID 426189-01. Philadelphia, PA.

Skogerboe, J. G., A. G. Poovey, K. D. Getsinger, W. Crowell, and E. Macbeth. 2008. *Early-season low-dose applications of endothall to selectively control curlyleaf pondweed*. APCRP Technical Notes Collection. TN APCRP-CC-08. Vicksburg, MS: US Army Engineer Research and Development Center.

Skogerboe, J. G., and K. D. Getsinger. 2002. Endothall species selectivity evaluation: Northern latitude aquatic plant community. *J. Aquat. Plant Manage.* 40:1-5.

Skogerboe, J. G., K. D. Getsinger, and L. M. Glomski. 2006. Efficacy of diquat on submersed plants treated under simulated flowing water conditions. *J. Aquat. Plant Manage.* 44:122-125.

Slade, J. G, A. G. Poovey, and K. D. Getsinger. 2008. Concentration/exposure time relationships for reducing biomass of sago pondweed (*Stuckenia pectinatus* (L.) Böerner) with two formulations of endothall. *Weed Technol.* 22:146-150.

Sprecher, S. L., K. D. Getsinger, and J. Sharp. 2002. *Review of USACE-generated efficacy and dissipation data for the aquatic herbicide formulations Aquathol® and Hydrothol®*. ERDC/EL TR-02-11. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Stokes, M. E., C. S. Davis, and G. G. Koch. 2000. *Categorical data analysis using the SAS® System*. 2nd ed. Cary, NC: SAS Institute, Inc.

Wade, P. M. 1990. The colonisation of disturbed freshwater habitats by Characeae. *Folia Geo.* 25:275-278.

Wersal, R. M., J. D. Madsen, and J. C. Cheshier. 2009. *Eurasian watermilfoil monitoring and mapping in Noxon Rapids Reservoir in 2009*. Geosystems Research Institute Report 5041.

Wersal, R. M., J. D. Madsen, B. R. McMillan, and P. D. Gerard. 2006. Environmental factors affecting biomass and distribution of *Stuckenia pectinata* in the Heron Lake System, Minnesota, USA. *Wetlands* 26:313-321.

Wersal, R. M., J. D. Madsen, T. E. Woolf, and N. Eckberg. 2010. Assessment of herbicide efficacy on Eurasian watermilfoil and impacts to the native submersed plant community in Hayden Lake, Idaho, USA. *J. Aquat. Plant Manage.* 48:5-11.

Woolf, T. E. 2009. Curlyleaf pondweed, Chapter 13.7 in *Biology and control of aquatic plants: A best management practices handbook,* ed. L. A. Gettys, W. T. Haller, and M. Bellaud, 125-128. Marietta, GA: Aquatic Ecosystem Restoration Foundation.

Woolf, T. E., and J. D. Madsen. 2003. Seasonal biomass and carbohydrate allocation patterns in Southern Minnesota curlyleaf pondweed populations. *J. Aquat. Plant Manage.* 41:113-118.

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14. ABSTRACT

Noxon Rapids Reservoir, Montana, is one of several large impoundments on the Lower Clark Fork River, stretching for over 48 km (30 miles) with a surface area of ~ 3,120 ha (7,700 acres). Management strategies were evaluated for their effectiveness in controlling invasive plant problems in the reservoir, specifically with Eurasian watermilfoil and curlyleaf pondweed. A 3-year field program was developed to evaluate the effectiveness of aquatic herbicides to selectively control the invasive plants.

The herbicide endothall (Aquathol® K) was applied to four plots totaling 5.5 ha (13.6 acres) at 3000 µg ai/L (3 ppm); diquat (Reward®) applied to four plots totaling 3.3 ha (8.1 acres) at 370 µg ai/L (0.37 ppm); and a combination of both products was applied to four plots totaling 4.7 ha (11.5 acres), with endothall at 1500 µg ai/L (1.5 ppm) and diquat at 190 µg ai/L (0.19 ppm). Herbicides were applied by boat using a variable-depth injection system. Aqueous herbicide dissipation was monitored in selected plots. Bulk water exchange processes were also measured. Quantitative surveys were conducted in each plot to assess the plant community at pretreatment, and at 6 weeks and 52 weeks post treatment.

Treatments provided significant reductions in Eurasian watermilfoil (59-69%) and curlyleaf pondweed (40-60%), through 52 weeks post treatment. Both products provided some degree of selective control, with a variety of native plants surviving the treatments.

15. SUBJECT TERMS

Aquatic herbicides	Diquat	Herbicides
Curlyleaf pondweed	Endothall	Invasive plants
	Eurasian watermilfoil	Noxon Rapids Reservoir
		Water exchange processes

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